Spinal pain and postural sway.

Is there a relationship?

By

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Doctor of Philosophy

of

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I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institution.

[Signature]

Alexander Ralph Ruhe
Postural stability is an important component in maintaining upright stance and balance during normal daily movements and activities. Postural stability is also an important factor in the elderly where balance disability may increase the risk of falls and subsequent injury. In sport, problems with balance may lead to serious injuries. Thus, postural stability has important implications in rehabilitation and sports.

Many different methods exist today for assessing postural sway. Centre of pressure (COP) evaluation is a frequently used method of measuring this stability and gain insights into potential pathological mechanisms e.g. in association with pain. This is possible as the COP signal is proportional to ankle torque, a combination of descending motor commands as well as mechanical properties of the musculature around.

Over the last decades, postural sway has been most commonly evaluated by using spatial measures such as sway distance, velocity and area traversed based upon sequential locations of the COP in the plane of the force platform. However, despite its common usage, important clinical aspects of the COP measurements such as its potential suitability for clinical monitoring purposes in pain patients remained unaddressed. Several literature reviews were conducted that identified relevant gaps in current knowledge to focus our research.

This led to the following primary research questions:

a) Can a best evidence experimental setup be identified that is suitable for spinal pain sufferers?

a) Is there a relationship between pain intensity and the COP excursions?

b) Are there alterations in postural sway associated with diminishing pain?
Based on a systematic review of the literature the following experimental protocol was developed: Three measurements of 90sec each were conducted in bipedal narrow stance with closed eyes at a sampling frequency of 100Hz. We selected the COP parameters 90% circle diameter as a descriptor of sway area and mean sway velocity as it has shown its discriminative value for various pain conditions.

The prospective part of this thesis was preceded by pilot studies that confirmed the excellent reliability of the selected experimental setup for mean sway velocity in antero-posterior (AP) and the medio-lateral (ML) direction (ICC_{2,k} 0.85-0.89, 95% CI 0.63-0.97, SEM 0.66-0.78) and 90% circle diameter (ICC_{2,k} 0.80, 95% CI 0.54-0.94, SEM 0.89). Later on, very similar values were observed for sway data obtained from the symptomatic groups.

The experimental setup was found to be safe and a sub-sample of predominantly low back pain patients (n=20) reported no difficulties complying with the postural tasks involved. Furthermore, no effects of learning or fatigue could be demonstrated in 10 healthy individuals either during inter-session (10 consecutive measurements) or intra-session (three times 3 measurements at 2-3 day intervals). No adverse incidents associated with the measurements occurred in approximately 1500 measurements.

By enrolling age matched healthy individuals as a control group (n=77), reference values for the included COP parameters were established to which all subsequent data obtained from symptomatic individuals could be compared.

A total of 210 patients were enrolled subdivided into three groups for non-specific neck, mid back and low back pain. A physical examination was conducted for all pain sufferers, who were asked to rate their pain intensity on a NRS-11 scale. The associated disability was assessed by means of the Disability Rating Index. Depending on the reported severity of their
complaint, the symptomatic individuals were subdivided into seven pain intensity groups (NRS 2-8) for each of the painful regions: low back (n=77, n=11/group), mid back (n=63, n=9/group) and neck (n=70, n=10/group).

The symptomatic participants exhibited greater postural sway than healthy controls. As a general trend, a statistically significant increase was reached beginning at about NRS score 4 for all three pain regions. Depending on the COP parameter and painful region, significant differences between individual NRS levels were reached about every 2-3 NRS levels.

Significant differences in COP excursions between mid back, low back and neck pain sufferers could be identified. However, in the light of the expected inter-subject variability in pain perception as well as the low number of participants per NRS group this conclusion warrants caution.

A major finding from a univariate regression analysis was a linear relationship between pain intensity and the COP parameters (p<0.001) for all painful regions, while a multivariate regression analysis showed that other variables such as age, gender, height, weight and BMI did not have a statistically significant effect on postural sway.

This close relationship was maintained even with diminishing pain levels after a course of manual therapy treatments conducted in a group of low back (n=38) and neck pain patients (n=36). In this instance three measurements and interventions were performed at 3-4 day intervals. With few exceptions, the follow-up COP measures in connection with specific pain intensities did not show a significant difference in postural sway compared to reference values for identical NRS levels at baseline.
In addition, a similar linear relationship between pain intensity, the COP sway parameters and the patient's disability ratings was identified for all painful regions.

At the same time, a clear trend towards predominant sway in the medio-lateral direction was observed with increasing pain intensities, until 70% of sway occurred in ML direction at NRS score 8. In comparison, healthy controls showed a nearly equal sway distribution between AP (52%) and ML (48%) direction.

In the absence of learning effects, the reduced COP excursions with decreasing NRS scores in subacute and chronic pain sufferers further suggests that pain interference rather than long-term neuro-physiological adaptations (such as central sensitization) are the primary causative factor for increased sway.

Our findings may have clinical implications for COP measures in patients with significant pain. These include routine sway analyses as an objective outcome measure during the rehabilitation and treatment process. It also stresses the importance of an initial focus on pain regulation rather than proprioceptive training.
ACKNOWLEDGEMENTS

My path towards undertaking and completing a higher qualification by research has been reinforced and received direction and support from a wide range of individuals along the way.

Since undertaking the studies towards this PhD, my supervisors were a tremendous source of knowledge, energy and support. Dr Bruce Walker from the School of Chiropractic and Sports Science at Murdoch University and Dr René Fejer from the Spine Centre of Southern Denmark and University of Southern Denmark provided me with high levels of autonomy and yet they were always available as sources of information. Especially with Dr Fejer the "quick chat" we would arrange were sure to turn into an in-depth discussion lasting for hours into the night. In these years both have provided a strong research methods background, coupled with a keen analytical approach to the research questions investigated as well as an extremely valuable critique of all my written material. At the same time, they also reminded and encouraged me not to disregard my private life, especially during the rather frantic later stages towards completion. The combination of these two supervisors, both with different styles and approaches to the rigors of completing a PhD, has provided an excellent basis to further develop from this point and I am deeply grateful for this. While they contributed greatly, I bear full responsibility for the content of this thesis and any mistakes associated with it.

The Praxis für Chiropraktik Wolfsburg provided a highly supportive environment which allowed the combination of clinical work and research activity. The thesis would not have been possible without the help of my colleagues Alexander Steinbrenner DC and Tino Bos DC who provided a room for the measurements, helped with the literature search and conducted the physical examinations, patient documentations and treatments during the prospective part of this thesis.
In addition, I am very grateful for the invaluable and essential support by the clinic staff during the process of patient recruitment. Each of them agreed to spend additional time in clinic copying and distributing information material and in doing so, they freed up valuable time for me to pursue other tasks associated with the conduct of the experiments.

External assistance also contributed to this project and I am indebted to the reviewers of the publications arising from this project. Based on long experience in the field of postural sway analysis, their valuable input added depth to the discussions and further strengthened the final manuscript of this thesis.

Another important source of support was my family. While not being directly involved in the conduct of this thesis, they contributed substantially by simply listening to my thoughts when I constantly developed and dismissed new ideas, offering encouragement and giving me the feeling that they were with me along the way. My father and sister also shared anecdotes from their own experience completing research doctorates that were both inspiring and reassuring.

Finally, I thank my wife Sina for encouraging, supporting and enduring my endeavors over these past years. I cannot count the times I apologized for my absence of thought and moods when I returned once again late and exhausted. At the same time, there has been nothing better than coming home after a long day of clinic and research when things have not always gone well, knowing that a welcoming reception will be given and that the day's problems will soon be put into context and perspective. Sina, you have provided me with tremendous support and inspiration and I believe it is fair to say that I would not have reached this point without you.
PUBLICATIONS ARISING FROM THIS THESIS

Papers


Posters and Abstracts


Ruhe A, Fejer R, Walker BF. Inter- and intrasession effects of learning and fatigue on center of pressure measures in healthy individuals. European Chiropractors' Union, ECU Convention, 02-04 June 2011, Zurich, Switzerland.

Ruhe A, Fejer R, Walker BF. Associations between non-specific manual interventions and the magnitude of COP excursions in NSLBP patients. European Chiropractors' Union, ECU Convention, 02-04 June 2011, Zurich, Switzerland.


Ruhe A, Fejer R, Walker BF. Inter- and intrasession effects of learning and fatigue on center of pressure measures in healthy individuals. Chiropractors and Osteopaths College of Australasia, 10th Biennial Conference, 8-9 October 2011, Melbourne, Australia.


**Podium presentations**


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<tr>
<td>A/D</td>
<td>analogue-to-digital</td>
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<tr>
<td>AMTI</td>
<td>Advanced Mechanical Technology Incorporated</td>
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<tr>
<td>AP</td>
<td>anterior-posterior</td>
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<td>ART</td>
<td>active release technique</td>
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<td>BBS</td>
<td>Berg balance scale</td>
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<tr>
<td>BOS</td>
<td>base of support</td>
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<td>C</td>
<td>compliant surface (on force platform)</td>
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<tr>
<td>CI</td>
<td>95% confidence interval(s)</td>
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<td>CLBP</td>
<td>chronic low back pain</td>
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<td>COP</td>
<td>center of pressure</td>
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<td>COM</td>
<td>center of mass</td>
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<td>COG</td>
<td>center of gravity</td>
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<td>CNS</td>
<td>central nervous system</td>
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<td>CV</td>
<td>coefficient of variation</td>
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<td>DCG</td>
<td>German Chiropractors' Association</td>
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<td>DFA</td>
<td>detrended fluctuation analysis</td>
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<td>d or dist</td>
<td>distance</td>
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<td>DRI</td>
<td>disability rating index</td>
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<td>DSN</td>
<td>diabetic sensory neuropathy</td>
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<td>EC</td>
<td>eyes closed</td>
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<td>EMG</td>
<td>electromyography</td>
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<tr>
<td>EO</td>
<td>eyes open</td>
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<tr>
<td>F</td>
<td>firm surface (on force platform)</td>
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<td>FABQ</td>
<td>fear avoidance belief questionnaire</td>
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FD  fractal dimension

G  gravity

GC  generalizability coefficient

GF  gauge factor

GRF  ground reaction force

H  Hurst-component

HVLA  high velocity, low amplitude (manipulative thrust)

ICC  intra-class correlation coefficient

L  length

LB  large base (forceplate)

LBP  low back pain

LEI  lower limb injury

$M_{x,y,z}$  moments acting on the platform

ML  medio-lateral

MMDC  minimal metrical detectable change

mod  moderate

mPos  mean position

ms  milliseconds

mValue  mean value

mVel  mean (sway) velocity in mm/s

n  number

NB  narrow base

NDI  neck disability index

Nm/rad  unit (kinetics) for torque

NP  neck pain

NRS  numeric rating scale (NRS-11)
<table>
<thead>
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<tr>
<td>ns</td>
<td>not significant</td>
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<tr>
<td>NSLBP</td>
<td>non-specific low back pain</td>
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<tr>
<td>NSMBP</td>
<td>non-specific mid back pain</td>
</tr>
<tr>
<td>NSNP</td>
<td>non-specific neck pain</td>
</tr>
<tr>
<td>PASW</td>
<td>predictive analytics software</td>
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<tr>
<td>PCC</td>
<td>Pearson's correlation coefficient</td>
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<td>PIR</td>
<td>post-isometric relaxation</td>
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<td>RC</td>
<td>reliability coefficient</td>
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<tr>
<td>RMS</td>
<td>root mean square</td>
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<tr>
<td>ROM</td>
<td>range of motion</td>
</tr>
<tr>
<td>RTA</td>
<td>road traffic accident</td>
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<tr>
<td>SD</td>
<td>standard deviation</td>
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<tr>
<td>SDA</td>
<td>stabilogram diffusion analysis</td>
</tr>
<tr>
<td>sec</td>
<td>second(s)</td>
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<tr>
<td>SEM</td>
<td>standard error of measurement</td>
</tr>
<tr>
<td>SI</td>
<td>stability index (COP parameter)</td>
</tr>
<tr>
<td>SL</td>
<td>single leg</td>
</tr>
<tr>
<td>SLR</td>
<td>straight leg raise (orthopedic test)</td>
</tr>
<tr>
<td>SMT</td>
<td>spinal manipulative therapy</td>
</tr>
<tr>
<td>SPSS</td>
<td>statistics package for the social sciences</td>
</tr>
<tr>
<td>TEA</td>
<td>total excursion area</td>
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<tr>
<td>VAS</td>
<td>visual analogue scale</td>
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<tr>
<td>vel</td>
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INTRODUCTION
CHAPTER 1

Introduction

1.1. Background

Postural stability is an important component in maintaining an upright position and balance during movements and daily activities. It is also an important factor in the elderly where balance disability may increase the risk of falls and subsequent injury [1-3]. In sport, problems with balance may lead to serious injuries [4]. Thus, postural stability has important implications in injury prevention, sports and rehabilitation and accordingly merits investigation.

Human upright stance is inherently unstable because the influence of gravity continuously endangers body equilibrium [5]. Even a small sway deviation results in torque due to gravity that accelerates the body further away from the upright position, an effect that is primarily countered by a corrective torque exerted by the feet against a stable support surface [6].

Many different approaches exist today for the assessment of balance performance [7], and centre of pressure (COP) evaluation is a frequently used method of measuring postural sway and any associated pathological mechanisms. In simple terms, COP is the point at which the pressure of the body over the soles of the feet would be if it were concentrated in one spot.

This is possible as the COP measured as a signal is proportional to ankle torque, a combination of descending motor commands as well as mechanical properties of the musculature around [8]. Measurements of the displacement of the COP in quiet standing have been used to evaluate and characterize the postural control system and its changes following
neurological impairment [9], ageing [10-12] and the application of orthotics and prosthetics [13].

In order to fully appreciate the experimental results and conclusions reported later in this thesis, it is important to gain a basic understanding of the proposed mechanisms underlying postural control.

1.2. Definitions of center of pressure and center of mass

A definition of the two most commonly encountered terms in this thesis is necessary. Body sway is associated with deviations in the location of the center of mass (COM) in space and the COP on a support surface [14].

COP refers to the point of application of consequent vertical forces acting on the support surface. It can be defined as the position of the global ground reaction force vector that accommodates the sway of the body [15].

COM, sometimes referred to as center of gravity (COG), is a point equivalent of the total body mass in the global reference system [16] and is commonly accepted to lie around the S2 vertebral level in normal upright posture [17]. The COP position differs from the COM position as the latter indicates a global position of the body where COP includes dynamic components due to body acceleration [18] (Figure 1.1).
1.3. Postural control in quiet stance

There are three main requirements for postural control: 1) to support the head and body against gravity, 2) to maintain the COM position within the base of support (BOS) to stabilize body during movement and normally occurring postural sway, and 3) to anticipate postural responses and integrate these with voluntary movement [19]. To achieve these three goals, the postural control system requires inputs and contributions from many subsystems as will be outlined later on.

Typically, postural stability is defined as the ability to maintain or control the COM in relation to the base of support (BOS) to prevent falls [20]. The mean BOS for a healthy individual during quiet standing with eyes open is shown below [18]. The area engulfing the COP excursions only consists of less than 0.05% of the BOS (Figure 1.2).
Maintaining balance is the process by which postural stability is maintained. The ability to maintain a posture, such as balancing in an upright standing position, is operationally defined as static balance [21]. Since the human body is never absolutely stable, a control system is required to stabilize the body, hence the terms postural control and balance control [22].

Motor behavior is a natural and continuous superimposition of movement periods. It generally involves large and rapid displacements of focal body segments to subserve goal-directed actions, and posture periods, made of small and slow displacements of the whole body to achieve postural orientation and maintain postural equilibrium [23]. This thesis will focus on the latter.

A low amplitude, apparently random body sway, is continuously present during quiet stance and many factors such as age and health status play a role in maintaining balance [24]. Much
has been written about the body systems contributing to balance and it would exceed the scope of this chapter to repeat this in great detail here. Instead, only a brief overview is given.

Postural control requires a complex interaction of musculoskeletal and neural systems [25]. Musculoskeletal components include such factors as muscle properties, joint range of motion and biomechanical relationships between linked body segments [26] (Table 1.1).

**Table 1.1:** Properties of the three motor systems in balance movement control

<table>
<thead>
<tr>
<th>System property</th>
<th>Reflex</th>
<th>Automatic</th>
<th>Cortical</th>
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<td>Spinal</td>
<td>Brainstem/Subcortical</td>
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<td><strong>Activation</strong></td>
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<td>External stimulus</td>
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<td><strong>Role in postural control</strong></td>
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<td><strong>Latency (in ankle)</strong></td>
<td>Fixed 35-45 ms</td>
<td>Fixed, medium-latency (mean 95 ms)</td>
<td>Variable ≥150 ms</td>
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<td></td>
<td></td>
<td>long-latency (mean 120 ms)</td>
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Adapted from Jacobsen et al. [27]

Neural components that contribute essentially to postural stability include motor processes organizing neuromuscular synergies, sensory/perceptional processes that organize and integrate visual vestibular and somatosensory systems and higher level processes essential for mapping sensation to action [21]. These also ensure anticipatory aspects of postural control as will be outlined later on.
There is broad consensus on the correlation between COM migration and corrective COP excursions and various theories regarding the mechanisms countering torque due to gravity have emerged. This chapter gives a review of the current evidence.

### 1.3.1. Ankle strategy and hip strategy

It is generally accepted that humans are able to select distinct strategies to maintain balance depending on the magnitude of postural disturbances [28-30]. For small disturbances in postural equilibrium, the amplitude of sway angles will be small and the ankle strategy will be adopted in which only ankle torque is considered to contribute to reducing sway angles [31]. Muscle activity of the gastrocnemius in response to postural perturbations begins after about 90-100ms, followed by the hamstrings 20-30ms later [32]. Activation of the gastrocnemius produces a plantar flexion torque that first slows down, and then reverses anterior motion [21]. For larger disturbances causing large amplitude of sway angles, hip strategy will be adopted. Here, hip torque is generated in coordination with ankle torque to maintain upright stance [28].

Winter et al. also indicated that in bipedal narrow stance, maintaining balance in anterio-posterior (AP) direction is totally under ankle control, whereas medio-lateral (ML) balance is controlled by hip strategy [33]. When the ankle strategy is applicable, a single-link inverted pendulum is considered sufficient to represent the human body [34]. In contrast, the human body should be considered as a multi-link inverted pendulum when the hip strategy is applied [28].

For the purpose of this thesis, only control mechanisms associated with ankle strategy will be considered as it is exclusively concerned with unperturbed, quiet bipedal stance.
1.3.2. Passive and active postural control

Passive torques as a postural control mechanism are assumed to stem from intrinsic tissue mechanical properties such as stiffness or viscosity, and to act without time delay [35]. In contrast, active control torques are generated by active muscle contraction [36]. A time delay due to sensory transduction, transmission, processing, and muscle activation is necessarily involved in this form of control torque [37].

Winter et al. [38-40] developed a control model for quiet stance in which a stiffness control strategy was adopted. The human body was assumed to behave like an inverted pendulum, with ankle joint torque being proportional to the angle of the pendulum from vertical.

This model further predicted that the COP oscillates in phase with the COM during body sway. The inverted pendulum thereby relates the controlled variable (COM) to the controlling variable (COP) [41]. In basic terms, COP tracks the COM oscillating either side of it in order to maintain it in some central position between the feet [40]. While COP theoretically completely coincides with COM at low sway frequencies below 1Hz [16], its displacement during compensatory sway always exceeds that of the COM. Lafond et al. [42] demonstrated the relationship between COP and COM during quiet stance. Their postural sway signals have shown to be closely related under both eyes open and eyes closed conditions ($r=0.94-0.98$) [43] (Figure 1.3).
Before going into more detail about the proposed control mechanisms, it is worth appreciating the basic interaction between COP and COM migrations in upright stance first. The following figure illustrates this concept, where $d_{\text{COM}}$ and $d_{\text{COP}}$ refers to the distance between the ankle joint and the position of the COM and COP respectively, GRF stands for ground reaction force. As long as the COP position is ahead of the COM, a leaning response will regain equilibrium (A). On the other hand, if COM position exceeds that of the COP then a step response is necessary to regain balance or a fall occurs (B) (Figure 1.4).
Figure 1.4: The interaction between COM and corresponding COP excursions

Figure 1.5 further illustrates how changes in COM position in response to an external perturbation occur in quiet standing. The initial position of the COM is at the level of the midfoot and indicated by the small triangle. In Trajectory 1, the combined change in anterior COM position and velocity remains small enough so stability can be maintained by shifting the COP position without changes in the BOS.

In contrast, in Trajectory 2 the magnitude of COM velocity and position exceeds the limits of stability and necessitates a step response to recover stability. In this case, the COM position moves anterior to the toes, thereby making a sufficiently large compensatory change in COP position impossible.
Motivated by the experimental observation that the oscillation of the COM is in phase with the COP excursions, and the theoretical consideration that such phase lock was incompatible with the afferent and efferent delays associated with active control of balance, Winter et al. have advanced their initial stiffness model [40] to describe the complex postural stabilization problem [38]. Here, the central nervous system (CNS) sets the muscle tone at specific balance control sites in a way that the stiffness constant is sufficient to control the large inertial load against the gravitational force attempts to topple the pendulum system. They thereby argue that stabilization of quiet standing is achieved by the stiffness of ankle muscles alone without any significant active or reactive component, except for background setting of the stiffness parameters. We may refer to this mechanism as passive torque.

Based on borderline sensory thresholds and the fact that afferent and efferent neuromuscular delay estimates between COM and COP could not be experimentally demonstrated [40], a purely reactive muscle control appeared unlikely at that time. This view was strengthened by
the assumption that latencies in the motor loop and low pass characteristics of the biological 
muscle limit the effectiveness of active and reactive control mechanisms [45]. It drew further 
support from the equilibrium point hypothesis [46] where well-coordinated, multi-joint 
movements are executed in the absence of complex computation by the brain, with the use of 
spring-like muscle properties and peripheral neural feedback loops. The validity of this theory, 
however, is still subject to debate as well [47, 48].

Winter et al. [38] also directly estimated muscle stiffness from ankle joint torque and sway 
angle and reported an average correlation coefficient of $r=0.92$. Furthermore, high $r$-values 
between COP-COM and COM acceleration in both AP and ML directions were reported [49] 
which appeared consistent with the simulation results from the proposed stiffness control 
model.

The ankle stiffness model has therefore served as the basis of many postural control models. 
The advantage of this model, and probably a reason for its popularity, is that if most postural 
sway takes place around the ankle joint, then the position of the head in space, of the COM in 
space, or of any other point of the body in space are related to each other trivially. This would 
simplify the integration of sensory information from multiple sources.

However, more recently the validity of the stiffness control model has been questioned and 
criticized as being overly simplistic [35, 50-53]. It has been argued that passive torque alone is 
not sufficient to stabilize the body as an inverted pendulum [54-57], and that additional active 
torque is necessary.

Experimental evidence suggests that the lowest ankle stiffness to support a stiffness-only 
inverted pendulum model under normal circumstances would be close to 2000 Nm/rad [58, 
59], where Newton meter per radian is an expression of the torsional stiffness [60]. However,
direct measures of ankle stiffness show to be around 500 Nm/rad [54, 55] and therefore far below the theoretically required value. Their results further suggested that the in-phase relationship between COP and COM trajectories was determined by physics, not by the control pattern.

In addition, it has been shown that the inverted pendulum body can be stabilized even when intrinsic stiffness was low, again indicating that muscle stiffness alone may not be the dominant factor in postural control. Furthermore, the analysis of sway magnitude indicated that intrinsic stiffness contributed little to maintaining balance [53].

Recently, direct measurements of intrinsic ankle stiffness were conducted and this intrinsic ankle stiffness was compared to the critical stiffness necessary for stabilizing the inverted pendulum [61]. It was concluded that if the measured stiffness is below the critical stiffness level, an active stabilization mechanism is required to compensate the inadequate stiffness. Otherwise active stabilization is not necessary. The results showed that intrinsic ankle stiffness during quiet standing reached only 64±8% of the critical stiffness, an additional active neural control therefore appears likely.

Other experimental results are in agreement and lend further evidence to the dominant role of active control torque in balance control [51]. Here, stimulus-response data for bipedal stance was collected with a simple feedback control model being used. Postural stiffness, damping and feedback time delay defined in the model were estimated in such a way that the transfer functions could best match the collected stimulus-response data. The passive intrinsic stiffness and damping parameters were only 10% of the value of active stiffness and damping parameters.
We may therefore conclude that while the inverted pendulum model itself is widely accepted, postural control cannot be maintained by passive torque alone and active torque modulated by neural control may play a dominant role.

1.3.3. Feedback and feedforward control mechanisms

Passive stabilization is unlikely to be robust and stable in the face of transmission delays and low levels of muscle stiffness [62]. Following the argument from the previous section, the role of neural control by means of feedback or feedforward mechanisms needs to be discussed. There is still as much debate regarding their respective role and importance.

The experimental and simulation results of numerous studies have shown that active joint control torque is generated according to feedback information about body orientation [6]. Based on an upright reference position obtained from the sensory systems, such as force feedback from Golgi tendon organs and position and velocity feedback from multiple muscle spindle organs, movement cues about the deviation of the body lead to the generation of corrective controls to resist the deviation of body position away from upright [51, 63, 64].

However, as with most aspects of postural control, the true control strategy is still an object of discussion and controversy and exactly how the neural control in humans works remains unknown in most respects. It is also a rather complex topic and coverage in detail would exceed the scope of this thesis.

The intrinsic feedback due to mechanical properties of ankle muscles operates with a zero delay in the short-term in order to slow down the fall of the inverted pendulum. As explained earlier, the muscle stiffness itself is not necessarily enough to sufficiently stabilize the body if
the critical value is reached [8]. As demonstrated by Peterka [51], a feedforward control mechanism is therefore often considered to be involved in postural control. This refers to the ability to predict an external input or upcoming behaviors and generate a corresponding active control torque to stabilize the body [29, 58, 65]. Therefore, two synergistic phenomenon need to be considered in the stabilization of standing posture: A neuromotor component which anticipates COM oscillations and a mechanical component related to muscle stiffness as previously outlined.

There is robust evidence for this feedforward component of postural control [29, 58, 59]. Activity of the lateral gastrocnemius muscle activity measured during quiet stance is positively correlated with AP motion of the COM and its muscle contractions, which provided the control torque, preceded COM position change by about 200ms [29]. Based on these findings, neural control is considered to be able to generate control torque in anticipation of an upcoming position of the COM. It has therefore been suggested that a feedforward control mechanism is responsible for stabilizing the human body during quiet standing. This was also recognized by other research [65].

It also has been observed that a comparison of anterior-posterior oscillations of the COP and the electromyographic (EMG) recording of the antigravity muscles pointed to moment-to-moment involvement of a system of stance control based on timely produced muscle impulses [58]. Further studies demonstrated that the motor-neuron activation during quiet stance varied since EMG activity of ankle muscles was modulated in anticipation of postural sway [58, 59].

There is evidence that this feedforward muscular control is altered in both acutely induced pain [66] and patients with pain related to disc herniations [67], leading to a delayed muscle recruitment [68]. This may then lead to a reduced ability to predict an external input (e.g. involuntary sway) and generate a corresponding active control torque. However, no consistent
change in feedforward activation could be observed for different muscle groups and the mechanisms behind this remain unclear [66].

The importance of the feedforward system, however, was recently challenged and active torque generated by feedback control mechanisms considered to be the dominant contributor to quiet stance control [51]. Masani et al. [69] simulated human quiet stance using the inverted pendulum model. The simulated COM position, velocity and ankle joint torque were compared with those from the experiments. The feedback controller was able to stabilize bipedal quiet stance even when the time delay was as large as 185ms, and generate the preceding motor command that was observed experimentally. The data demonstrated that a feedforward control mechanism may be not necessary for postural control (Figure 1.6).

**Figure 1.6:** Basic principles of human stance control
Recent studies indicate that inverted pendulum models of quiet stance control and the associated ankle strategy may represent an oversimplification in itself [71-73]. Alexandrov et al. [71], for example, provided data suggesting that the ankle, knee, and hip joints are coordinated separately. While it was agreed that what he referred to as ankle “Eigenmode” involves predominately ankle motion, motion of the knee, hip and trunk also make important contributions to the control of upright stance. The inverted pendulum model, however, remains widely accepted today.

Finally, the assumption by some researchers that the weights of sensory information in different test conditions remains constant has been challenged by other recent investigations which showed the contributions of different sensory systems to postural steadiness can be re-weighted when the goal of a movement task or the environmental context changes [74, 75]. It has been demonstrated, for example, that the contribution of proprioceptive input from the ankles is increased under visual deprivation [64, 75] and that the focus of proprioceptive sensitivity changes from the trunk to the ankle with aging [76].

1.3.5. Summary

Postural control remains a complex and intensely debated topic. Overall, the evidence reviewed in this section suggests that the postural control system should be considered a feedback rather than a feedforward control system generating and coordinating active torque.

Amongst other things, this thesis will attempt to investigate whether and how the mechanisms described above are affected by pain and what consequences arise for postural sway. This will be done using COP measures obtained from a force platform as a descriptor of body sway.
1.4. Force platforms

1.4.1. Brief historical background

The assessment of postural sway on some form of measuring device is not as recent an invention as one might assume. The first measuring device is usually attributed to the French physiologist Marey who performed sway assessments in 1895 [77]. This system used air filled tubes which could register forces. Force sensitive platforms were constructed to react to both vertical and horizontal forces. The apparatus of Amar (1916) using rubber bulbs and the platform with springs built by Elftman (1938) are just some other examples [78].

Since then, more sophisticated designs have emerged. The first commercial force platforms were manufactured by Kistler in 1969 and used a piezoelectric principle, in 1976 Advanced Mechanical Technology Incorporated (AMTI) introduced a platform based on a strain gauge system [79]. These two still remain the most popular types of platform worldwide, although others, like weigh scale based systems, have become commercially available.

1.4.2. How force platforms work

1.4.2.1. Piezoelectric systems

Piezoelectric force plates are based on the piezoelectric effect discovered by the Curie brothers in 1880 [80]. They use piezoelectric crystals (e.g. quartz) and the deformation of this crystal under load is the basis for signal generation [81]. When deformation takes place this generates what is known as an electronic dipole moment, which generates an electronic current [82]. As the crystals generate their own current, no external power supply is required. The alignment of the piezoelectric crystals on each pylon determines the coordinate system of the forceplate which allows data generation [83].
In contrast to strain gauge systems, piezoelectric force plates generate 8 channels of analogue output, none of which contain any information of the moments acting on the platform (Mx, My, Mz) [83] as described later. However, these can be calculated if the position of the COP in AP and ML direction is known [84].

Although piezoelectric force-plates have the advantage of sensitivity and natural frequency, they suffer from signal drifting after about 30sec of recording duration which can lead to measurement errors [83]. On the other hand, this signal drift only relevantly affects COP evaluation for sampling durations of more than or equal to 1 min and when the applied weight is less than 25kg [85].

1.4.2.2. Strain gauge based systems

Strain gauge platforms are generally less sensitive to high frequency activities (≥500Hz) compared to piezoelectric systems (≤1000Hz). However, for general use in static task conditions they are more than adequate.

Strain gauge force plates are based on the principle that when a force is applied to a structure, deformation takes place. Strain is the ratio of changes between the original dimensions and the deformed dimensions [86]. The strain is based on resistance provided to the electrical current from the power supply [87]. Invented in 1938 by Edward Simmons and Arthur Ruge, the most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern [88]. The gauge is attached to the force transducer of the platform. As deformation takes place during the measurements, the foil is deformed, causing its electrical resistance to change [89]. This allows the collection of COPnet data.
The strain gauges are grouped in triplets in the corners of the force-plate [87]. As the resistance is normally very small, the signals produced by strain gauge plates require amplification which can either take place in the platform itself or in a separate amplifier [83].

Strain gauge force-plates produce an output of 6 channels of analogue data relating to forces in x, y and z directions (Fx, Fy, Fz) and the moments in x, y and z (Mx, My, Mz). So, these platforms are quite simple in their output with a single analogue channel representing a single moment or force [90].

The principle of operation involves an external force (F), which when applied creates a reaction force generated by the load cells to retain equilibrium (∑F=0). Thus, when a force is applied to the forceplate, the load cells record the resulting equal and opposite (upwards) reaction force acting on the person [90, 91].

A total of 9 individual reaction forces are produced by the three components of each of the three loading cells. Applying standard mechanical analysis to these factors allows the resultant component reaction forces Fx, Fy, Fz to be calculated as follows [91]:

\[
\begin{align*}
F_x &= X_1 + X_2 + X_3 \\
F_y &= Y_1 + Y_2 + Y_3 \\
F_z &= Z_1 + Z_2 + Z_3
\end{align*}
\]  

(1.2.)

A visualization of the resulting calculated COP path of a mid-aged healthy individual over the course of a 90sec trial is shown as Figure 1.7.
1.5. Obtaining COP measures

Although the use of posturographic analysis of human COP sway pattern is not new, its use in a clinical context is still limited. A reason for this is that to date there has been no consensus regarding methods, techniques or data interpretation [92].

Postural sway observed in quiet standing represents the integrated output from the complex interaction between the balance systems mentioned above. As understanding of these balance mechanisms evolved over the last decades, the literature shows a large change in the study designs used to investigate COP migrations [92].

For the purpose of describing the ability to maintain postural equilibrium, various body sway parameters are used in clinical, sports and research practices. The selection of suitable COP
parameters depends on the methods to be used, as well as on the stationary or dynamic nature of the balancing task [93]. Accordingly, a broad variety of COP parameters have been developed to investigate different aspects of postural sway. As these and their impact will be described and discussed in depth in the following chapter, only a general overview is given here (Table 1.2).

Table 1.2: Selective list of posturographic parameters

<table>
<thead>
<tr>
<th>Domain</th>
<th>Parameter</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>Mean sway velocity</td>
<td>mm/s</td>
<td>Length of the trajectory of the COP over the support base divided by the measurement time.</td>
</tr>
<tr>
<td>Position</td>
<td>Mean position</td>
<td>mm</td>
<td>Center of COP position in AP and ML direction</td>
</tr>
<tr>
<td>Distance</td>
<td>Path length</td>
<td>mm</td>
<td>Length of the trajectory of the COP over the support base</td>
</tr>
<tr>
<td>Area</td>
<td>Sway area</td>
<td>mm²</td>
<td>Oscillation amplitude in the AP or ML direction. It is estimated by computing the ellipse which contains 90% of the data-points of the COP trajectory.</td>
</tr>
<tr>
<td>Frequency</td>
<td>Frequency (AP/ML)</td>
<td>Hz</td>
<td>Frequency bands that contain a fraction of the area under the amplitude spectrum of the posturogram in AP and/or ML direction.</td>
</tr>
<tr>
<td>Vector</td>
<td>Mean vector length of direction sway</td>
<td>mm</td>
<td>Mean distance of body sway in any direction (often subdivided in eight 45° sectors).</td>
</tr>
</tbody>
</table>

AP: anterior-posterior, ML: medio-lateral

1.6. The Metitur GB 300

1.6.1. Manufacturer

Metitur Ltd. was a Finnish company that was established in 1996 and went out of business in early 2011. To a great extent Metitur’s work in the area of force plates was based on scientific research carried out at the University of Jyväskylä, Finland.
1.6.2. Technical details

The Metitur GB300 forceplate used for this thesis has three strain gauges in force transducers in each corner that are sensitive to forces along the X, Y and Z axis (Figure 1.8).

**Figure 1.8:** The Metitur GB 300 as an example of a strain gauge based system

The force platform is connected to a computer through a three-channel amplifier and an analogue-to-digital (A/D) converter. The system uses a combination of two different filters for data processing. First, a median filter with a window length of seven data points is used to reduce impulse noise. Secondly, high frequency noise from both the measuring equipment and the A/D conversion is reduced by a low-pass filter with a cut-off frequency of 10Hz. The

- \( F_x, F_y, F_z \): The reaction forces along the respective coordinate axis.
- \( A_x, A_z \): The coordinates which identify the point of force application (COP)

Illustration: Alexander Ruhe
force transducers are situated at the corners of the equilateral triangular platform and vertical forces are registered (Figure 1.9).

**Figure 1.9:** The Metitur Good Balance GB 300

The technical details of this forceplate are as follows:

- **Weight:** Force platform with integrated electronics: 10.5 kg
- **Dimensions of force platform:** 800 mm * 800 mm * 800 mm, height 110 mm
- **Power supply:** 110-230 VAC/9 VDC, 3 W
- **Operating system:** MS Windows 2000 or higher
- **3-channel DC amplifier**
- **8-channel 12-byte analogue-to-digital converter**
- **Sampling frequency:** variable 50-500Hz
On the basis of the force signals from each corner, the system calculates the x (medio-lateral, ML) and y (antero-posterior, AP) coordinates of the COP affecting the platform. The error in the calculated x and y coordinates is ≤1.0 mm when the mass of the measured individual is at least 40 kg [94].

1.6.3. Validity and reliability of the GB300

The validity of the Metitur GB 300 has previously been demonstrated [95] and the system has been used in numerous studies published in high level international scientific journals [96-102].

As a part of the Medical CE Approval of the Good Balance system, Metitur developed a procedure for testing the precision of the GB 300 in detecting the location and movements of a well defined mass. The system was tested in both static and dynamic test conditions where a mass was moving in a standardized way on the platform. By mathematical calculations it was deduced how much the mass really moved during the tests, and this was compared with the amount of movement in x- and y-dimensions registered and calculated by the Good Balance platform, electronics and software [103]. The tolerance for error compared with the absolute amount of movement was measured as +/- 1% [94]. All units that left the factory were assessed in this way for quality control.

With regards to the reliability of COP data derived from the GB 300 platform, the results vary considerably depending on the specific experimental setups. Previously reported test-retest reliability in terms of intra-class correlation coefficients (ICC) ranged between 0.51-0.83 for the COP parameter mean sway velocity (mVel) [97]. Others reported correlation coefficients for mVel in medio-lateral direction ranged from 0.46 with eyes open (EO) and 0.36 with eyes closed (EC), to 0.70 (EO) and 0.68 (EC) in antero-posterior direction, and from 0.37 (EO) to
0.46 (EC) for the parameter velocity moment [96]. The results by Juha et al. showed ICCs for mVel of 0.64 in ML and 0.73 in AP direction with eyes open. Velocity moment showed lower reliability at ICC 0.39 [101].

These reliability results show wide variations between the studies. In the next chapter the impact of a broad range of factors on the reliability of COP measures that is likely to explain this variability will be explored and discussed.

1.7. The thesis

Although posturographic COP analysis is commonly used [104], there is a profound lack of standardization of procedures and understanding of possible associations between perceived pain intensity, disability, physical examination findings and postural stability.

After systematically reviewing the relevant literature, this thesis will attempt to establish a best practice experimental setup that is both reliable and feasible for testing pain sufferers. On this basis, several practical studies will be conducted. The aim is for the first time to provide a direct comparison of COP data from patients with different symptomatic body regions, pain intensities, disability levels and possible changes in postural sway magnitude associated with manual therapeutic interventions.
THE TEST-RETEST RELIABILITY OF CENTRE OF PRESSURE MEASURES IN BIPEDAL STATIC TASK CONDITIONS - A SYSTEMATIC REVIEW OF THE LITERATURE

CHAPTER 2

The test-retest reliability of centre of pressure measures in bipedal static task conditions

2.1. Background

Although COP recordings have been used for two decades, there are no comprehensive guidelines for an ideal experimental setup with regards to reliability of COP measures and experimental procedures that may allow broader inter-study comparison.

Before the planned experiments for this thesis may commence, it is necessary to evaluate the reliability of COP measures as recorded by a forceplate in general and the importance of specific factors, such as the duration of the measurement and the number of repetitions, in particular.

This literature review aims at identifying a best-practice methodology for bipedal static task COP measures. Once established, experiments can be conducted to test these in practice.

2.2. Aims

The aims of this systematic literature review are 1) to describe and assess the methodological procedures of studies of the most commonly used COP measurements and methods, 2) to determine the reliability of commonly used centre of pressure parameters in bipedal static task
conditions, and 3) to provide recommendations regarding standardized COP methods for use in our study designs.

2.3. Methods

2.3.1. Search strategy

A comprehensive search strategy was developed by identifying all potentially relevant search terms, categorizing these terms into specific search phases and subsequently combining them by using Boolean terms. This search strategy was designed to be used in seven different electronic databases. These were PubMed, MEDLINE, EMBASE, Web of Science, ScienceDirect, Digital Dissertations and the Cochrane library. These seven databases were considered comprehensive for the subject at hand. All databases were searched using the search strategy described above. Appropriate minor modifications to the basic search template were made to optimize the strategy in individual databases. Papers were limited to human studies published between January 1980 and February 2009. A hand search was also undertaken and included analyzing references cited in studies selected from the original online search. In addition, key authors were contacted directly for information and clarification where necessary.

2.3.2. Selection Criteria

Articles were limited to peer-reviewed journals and dissertations without restrictions regarding language. Wide inclusion and exclusion criteria for study designs were used in order to avoid limitation of potentially relevant papers.
The inclusion criteria were: Articles that were fully or partially concerned with the intra- and intersession reliability of COP data derived from bipedal static tasks on a force plate. For this systematic review, all COP measures, experimental setups and statistical models fitting these criteria were considered. No limitations of the type of patient demographics or health status applied.

We excluded studies with insufficient documentation of patient demographics or experimental setup. In addition, papers that were anecdotal, speculative or editorial in nature or studies that employed dynamic task conditions such as one-leg hopping, walking or some form of translation of the force platform were excluded.

If any title and abstract did not provide enough information to decide whether or not the inclusion criteria were met, the full text of the article was obtained and reviewed.

2.3.3. Data extraction and management

For the purpose of this review AR acted as the principal reviewer. A colleague (TB) was involved independently in the process of identifying relevant studies and did not participate in further analysis of the finally included papers. A third reviewer (AS) was used for a majority decision in case discrepancies between AR and TB were not reconciled by discussion. To standardize the procedure between the reviewers, the principal reviewer developed a detailed protocol sheet for critical appraisal by which general information on objectives, study design, participant’s demographics and outcomes were extracted. Each reviewer retrieved the information independently. A test was conducted with two articles similar but unrelated to the review question and the procedures discussed.
2.3.4. Assessment of methodological procedures

The reviewers specifically assessed the application, documentation and association of six individual items with regards to test-retest reliability. These were 1) subject demographics and morphology, 2) sample duration, 3) number of trial repetitions, 4) visual condition (eyes open or eyes closed), 5) foot position, and 6) type of platform surface (hard or compliant). Papers not describing the items need to be considered with caution as these are necessary for full understanding of a reliability study. The rationale for choosing these six factors was that they were considered particularly relevant for reliability outcomes in the available literature.

2.4. Results

2.4.1. Literature search results

Initially, the online search strategy identified 215 study abstracts which were screened individually by the reviewers. The application of inclusion/exclusion criteria by the reviewers on the titles and abstracts eliminated a further 162 papers. The most common reason for exclusion was not meeting the selection criteria like static or bipedal tasks. From the titles and abstracts of papers selected (n=53), full articles were reviewed and the same two reviewers (AR and TB) applied the inclusion criteria to the full text. Of these, 32 papers met the inclusion criteria and were included in this review. Eleven of these articles were added after the hand search of reference lists of included papers (Figure 2.1).
The selection process of suitable studies identified only minor variance between the reviewers. AR and TB initially disagreed on the inclusion of two papers, giving an overall agreement of 97%. The differences were documented and consensus reached after discussion with the third reviewer (AS).

2.4.2. Study results

2.4.2.1. Characteristics of participants and methods

About 30% of the studies (9/32) provided either insufficient description of the selection criteria for participants or none at all. No study described blinding of the examiners to the subject’s health status.

While about half the authors described the baseline demographics of participants in appropriate detail (18/32, 56%), only one study included a physical examination in order to validate their health status prior to study enrollment [105]. The other authors relied only on
self-reports or did not provide any description at all. Only four studies reported calibration procedures of the force-plate, mostly by means of a calibrated static load [106-109]. With regard to patient demographics, most studies (83%) enrolled mixed gender groups of healthy participants between 21-40 years of age. Demographics and health status of the participants for all studies are shown in Table 2.1.

### Table 2.1: Participant demographics and health status

<table>
<thead>
<tr>
<th>Study</th>
<th>Number</th>
<th>Gender</th>
<th>Age Range /SD</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>Health status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldie et al. [110]</td>
<td>28</td>
<td>14</td>
<td>14</td>
<td>28.1 (8)</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Hageman et al. [105]</td>
<td>A: 24</td>
<td>12</td>
<td>12</td>
<td>20-35</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td></td>
<td>B: 24</td>
<td>12</td>
<td>12</td>
<td>60-75</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Hill et al. [111]</td>
<td>17</td>
<td>17</td>
<td>0</td>
<td>69.5 (7)</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Le Cilar et al. [112]</td>
<td>25</td>
<td>13</td>
<td>12</td>
<td>19-32</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Letz et al. [113]</td>
<td>A: 8</td>
<td>4</td>
<td>4</td>
<td>20-40</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td></td>
<td>B: 15</td>
<td>15</td>
<td>15</td>
<td>23-60</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Mattacola et al. [114]</td>
<td>12</td>
<td>10</td>
<td>2</td>
<td>24.7 (3)</td>
<td>62.2 (7.5)</td>
<td>healthy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>164.8 (7)</td>
<td></td>
</tr>
<tr>
<td>Riley et al. [115]</td>
<td>A: 11</td>
<td>4</td>
<td>7</td>
<td>50.3</td>
<td>-</td>
<td>Healthy</td>
</tr>
<tr>
<td></td>
<td>B: 15</td>
<td>11</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>B VH</td>
</tr>
<tr>
<td>Samson et al. [116]</td>
<td>15</td>
<td>8</td>
<td>7</td>
<td>20-60</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Tákalá et al. [117]</td>
<td>18</td>
<td>9</td>
<td>9</td>
<td>38.7</td>
<td>69.5</td>
<td>173</td>
</tr>
<tr>
<td>healthy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moe-Nilssen [118]</td>
<td>19</td>
<td>15</td>
<td>4</td>
<td>22.9</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Benvenuti et al. [107]</td>
<td>A: 12</td>
<td>6</td>
<td>6</td>
<td>74.5</td>
<td>72.5</td>
<td>162</td>
</tr>
<tr>
<td></td>
<td>B: 12</td>
<td>6</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td></td>
<td>C: 12</td>
<td>6</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>mod. disequilibrium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>severe disequilibrium</td>
</tr>
<tr>
<td>Geurts et al. [119]</td>
<td>A: 8</td>
<td>4</td>
<td>4</td>
<td>44.3 (20)</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td></td>
<td>B: 8</td>
<td>4</td>
<td>4</td>
<td>24.9 (2.4)</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Mientjes et al. [120]</td>
<td>8</td>
<td>3</td>
<td>5</td>
<td>38.4</td>
<td>-</td>
<td>CLBP</td>
</tr>
<tr>
<td>Carpenter et al. [121]</td>
<td>49</td>
<td>29</td>
<td>20</td>
<td>19-34</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Chiari et al. [122]</td>
<td>12</td>
<td>6</td>
<td>6</td>
<td>26-40</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Schmid et al. [123]</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>24-32</td>
<td>-</td>
<td>healthy</td>
</tr>
<tr>
<td>Kitabayashi et al. [124]</td>
<td>220</td>
<td>112</td>
<td>108</td>
<td>20</td>
<td>60.7</td>
<td>167</td>
</tr>
<tr>
<td>healthy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rogind et al. [125]</td>
<td>12</td>
<td>12</td>
<td>0</td>
<td>25.8</td>
<td>60.0</td>
<td>166</td>
</tr>
<tr>
<td>healthy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lafond et al. [126]</td>
<td>7</td>
<td>4</td>
<td>3</td>
<td>67 (4)</td>
<td>65(17.5)</td>
<td>161 (12)</td>
</tr>
<tr>
<td>healthy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doyle et al. [108]</td>
<td>30</td>
<td>10</td>
<td>20</td>
<td>23 (5)</td>
<td>71 (12)</td>
<td>175 (9)</td>
</tr>
<tr>
<td>healthy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raymakers et al. [127]</td>
<td>A: 45</td>
<td>unclear</td>
<td>unclear</td>
<td>21-45</td>
<td>unclear</td>
<td>unclear</td>
</tr>
<tr>
<td></td>
<td>B: 38</td>
<td>unclear</td>
<td>61-78</td>
<td>unclear</td>
<td>unclear</td>
<td>healthy</td>
</tr>
<tr>
<td></td>
<td>C: 10</td>
<td>unclear</td>
<td>75-89</td>
<td>unclear</td>
<td>unclear</td>
<td>geriatric</td>
</tr>
<tr>
<td></td>
<td>D: 21</td>
<td>unclear</td>
<td>65-87</td>
<td>unclear</td>
<td>unclear</td>
<td>Parkinson's</td>
</tr>
<tr>
<td>Amoud et al. [128]</td>
<td>A: 90</td>
<td>33</td>
<td>57</td>
<td>19.7</td>
<td>65.3</td>
<td>175.0</td>
</tr>
<tr>
<td></td>
<td>B: 10</td>
<td>6</td>
<td>4</td>
<td>80.4</td>
<td>75.0</td>
<td>166.8</td>
</tr>
<tr>
<td>Doyle et al. [129]</td>
<td>15</td>
<td>8</td>
<td>7</td>
<td>19.9 (1)</td>
<td>72.2 (12.5)</td>
<td>168 (4)</td>
</tr>
<tr>
<td>healthy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In order to challenge postural control by modifying the integration of visual, vestibular or proprioceptive input, the included studies variously applied a selection or a combination of all three conditions (eyes open/eyes closed, firm/compliant surface, narrow/normal stance). About 78% of the trials were performed under both eyes closed (EC) and eyes open (EO) conditions. Most authors conducted between 2-5 repetitions of postural sway recordings (14/32, 44%). In addition, the majority of trials were conducted on the firm surface (26/32, 81%) of a force platform (Table 2.2.).

Table 2.2: Study characteristics

<table>
<thead>
<tr>
<th>Study</th>
<th>Condition</th>
<th>Parameters</th>
<th>Duration (sec)</th>
<th>Repetitions</th>
<th>Statistics</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldie et al. [110]</td>
<td>BP, tandem, EO/EC/F, narrow stance.</td>
<td>COP ML/AP Force AP/ML/vertical</td>
<td>32</td>
<td>2</td>
<td>LR</td>
<td>EO: ML 0.30, AP=0.11</td>
</tr>
<tr>
<td>Hageman et al. [105]</td>
<td>BP EO/EC/F, normal stance</td>
<td>COP sway area</td>
<td>20</td>
<td>2</td>
<td>ICC 3.4</td>
<td>EO: 0.91, EC: 0.97</td>
</tr>
<tr>
<td>Hill et al. [111]</td>
<td>BP EO/F, normal, narrow stance+ others</td>
<td>Dispersion Index (DI)</td>
<td>25</td>
<td>9x3</td>
<td>ICC 2.1</td>
<td>EO: normal ICC 0.55, CV 0.17, narrow ICC 0.27, CV 0.19</td>
</tr>
<tr>
<td>Study</td>
<td>Conditions</td>
<td>Measurements</td>
<td>Parameters</td>
<td>Method</td>
<td>ICC/CV</td>
<td>Reference</td>
</tr>
<tr>
<td>------------------------------</td>
<td>------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------------</td>
<td>---------</td>
<td>--------</td>
<td>-----------</td>
</tr>
<tr>
<td>Le Ciar et al. [112]</td>
<td>BP, normal stance EO/EC/F</td>
<td>SD COP ML/ AP, mVel, SD force AP/ML/vertical</td>
<td>10, 20, 30, 40, 50, 60</td>
<td>2</td>
<td>RC</td>
<td>SD ML: 0.81, SD AP: 0.86, mVel: 0.84</td>
</tr>
<tr>
<td>Letz et al. [113]</td>
<td>BP, narrow, EC/EO/F</td>
<td>Vel, SD path, RMS AP/ML, mean excursion AP/ML</td>
<td>60 (2x30)</td>
<td>2</td>
<td>PCC</td>
<td>EO/EC/F 60sec: RMS path AP/ML 0.28-0.79, SD range 0.50-0.83, Vel 0.85-0.92.</td>
</tr>
<tr>
<td>Mattacola et al. [114]</td>
<td>BP, normal stance, EO/EC/F</td>
<td>Sway index</td>
<td>10</td>
<td>10</td>
<td>ICC</td>
<td>EO: ICC 0.75, SEM 0.06, 95% CI 0.16-0.40, EC: ICC 0.06, SEM 0.26, 95% CI 0.13-0.87</td>
</tr>
<tr>
<td>Riley et al. [115]</td>
<td>BP, normal stance, tandem, EC/EO/F</td>
<td>Phase plane</td>
<td>7</td>
<td>2</td>
<td>PCC</td>
<td>Healthy subjects: COP ML 0.91, AP 0.78</td>
</tr>
<tr>
<td>Samson et al. [116]</td>
<td>BP, EO/EC/F narrow stance, tandem</td>
<td>Mean velocity</td>
<td>60</td>
<td>10</td>
<td>CV</td>
<td>EO: 9.46% (4.55-29.38), EC: 10.53% (3.68-24.28)</td>
</tr>
<tr>
<td>Takala et al. [117]</td>
<td>BP, EO/EC/F narrow stance</td>
<td>Mean Vel, area, frequency, amplitude</td>
<td>30</td>
<td>2x2</td>
<td>ICC</td>
<td>Short term: EO mVel 0.64, EC 0.56, area EO 0.55, EC 0.43, Long term: EO mVel 0.86, EC 0.77, area EO 0.44, EC 0.40</td>
</tr>
<tr>
<td>Moe-Nilssen [118]</td>
<td>BP, EO/EC/F narrow stance</td>
<td>RMS AP/ML</td>
<td>30</td>
<td>3</td>
<td>ICC</td>
<td>All parameters ICC &lt;0.60 EO/EC, CV (%) 19.2-25.2</td>
</tr>
<tr>
<td>Benvenuti et al. [107]</td>
<td>BP, LB/NB, F/C, EO/EC</td>
<td>Mean velocity, Quadratic fit AP/ML</td>
<td>40, last 15 recorded</td>
<td>3</td>
<td>ICC</td>
<td>Vel 0.51-0.75, ML 0.65-0.77, AP 0.82-0.83</td>
</tr>
<tr>
<td>Geurts et al. [119]</td>
<td>A:B, EO/EC/BV B: BP, EO normal stance</td>
<td>AP/ML RMS amplitude, RMS velocity</td>
<td>A: 3x20, B: 2x30</td>
<td>5</td>
<td>CV</td>
<td>RMS area: ML 36%, AP 33%, RMS vel: ML 35%, AP 20%, range ML 32%, AP 27%</td>
</tr>
<tr>
<td>Mientjes et al. [120]</td>
<td>BP, normal stance, EO/EC, F/C</td>
<td>AP/ML RMS, COP mean, MPF</td>
<td>unclear</td>
<td>3</td>
<td>ICC</td>
<td>EO: RMS AP 0.14, ML 0.54, EC: RMS AP 0.41, ML 0.89</td>
</tr>
<tr>
<td>Carpenter et al. [121]</td>
<td>BP, narrow stance, EO/F</td>
<td>RMS, MPF, MPoSD AP/ML</td>
<td>120 (8x15, 4x30, 2x60)</td>
<td>3</td>
<td>ICC</td>
<td>Pos ML: 0.86-0.91, AP: 0.75-0.85, SD pos ML: 0.32-0.73, AP: 0.32-0.73</td>
</tr>
<tr>
<td>Chiari et al. [122]</td>
<td>BP, normal stance EO/EC/F</td>
<td>mVel, FD, area, Diffusion &amp; Hurst coefficient (H)</td>
<td>50</td>
<td>10</td>
<td>ICC</td>
<td>mVel EO 0.83, EC 0.87, area EO 0.58, EC 0.70, FD EO 0.53, EC 0.80, SMP 0.20-0.79, NSMP 0.54-0.85</td>
</tr>
<tr>
<td>Schmid et al. [123]</td>
<td>BP, EO/F, normal stance</td>
<td>mVel, area, amplitude, MPF, Hurst</td>
<td>unclear</td>
<td>3</td>
<td>ICC</td>
<td>ICC: mVel 0.71-0.75, Ampl 0.36-0.37, area 0.55-0.62, MPF 0.13-0.21, H 0.21-0.39</td>
</tr>
<tr>
<td>Kitabayashi et al. [124]</td>
<td>BP, narrow stance, EO/F</td>
<td>34 parameters (e.g. area, mVel, RMS vel.)</td>
<td>60</td>
<td>3</td>
<td>ICC</td>
<td>ICC &gt; 0.70 all parameters, Vel most reliable: mVel AP/ML, RMS vel: 0.96</td>
</tr>
</tbody>
</table>

35
<table>
<thead>
<tr>
<th>Reference</th>
<th>Methodology</th>
<th>Measurement Parameters</th>
<th>Trials or Duration</th>
<th>ICC</th>
<th>CV</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rogind et al. [125]</td>
<td>BP, EO/EC/F, normal/tandem stance</td>
<td>Vel AP/ML, 100% square, Max Ampl., sway index</td>
<td>25</td>
<td></td>
<td>CV</td>
<td>CV: 0.13-0.23</td>
</tr>
<tr>
<td>Lafond et al. [126]</td>
<td>BP, 2 platforms Normal stance, EO/F</td>
<td>RMS, range, Vel, MPF, MedPF AP/ML, area</td>
<td>120 (30, 60,120)</td>
<td>9</td>
<td>ICC2.1</td>
<td>EO: mVel 2 trials 120s for ICC≥0.90. RMS and range 6-8 trials 120s for ICC≥0.90, mVel ML most reliable</td>
</tr>
<tr>
<td>Doyle et al. [108]</td>
<td>BP, EO/EC/F, normal stance</td>
<td>FD, range, peak vel AP/ML, TEA</td>
<td>10</td>
<td>3</td>
<td>ICC2.1</td>
<td>EO/EC/F AP/ML: ICC FD &gt;0.75, range 0.43-0.71, Vmax 0.12-0.58. EO/EC/C AP/ML: FD 0.62-0.90, range -0.28-0.72, Vmax 0.01-0.14.</td>
</tr>
<tr>
<td>Raymakers et al. [127]</td>
<td>BP, EO/F, narrow stance</td>
<td>Range, mVel, phase plane, area, DC</td>
<td>50</td>
<td>2</td>
<td>CV (%)</td>
<td>CV%; mVel 14, phase plane 18, area 25, DC 30, range AP 28, ML 19.</td>
</tr>
<tr>
<td>Amoud et al. [128]</td>
<td>BP, EO/F, stance unclear</td>
<td>Hurst exponent (SDA, DFA)</td>
<td>up to 30</td>
<td>4</td>
<td>ICC3. ?</td>
<td>ICC increases with time (10s&gt;5s&gt;2.5sec), only DFA (elderly) 10sec ICC≥0.75.</td>
</tr>
<tr>
<td>Doyle et al. [129]</td>
<td>BP, EC/EO/F, normal stance</td>
<td>SD AP/ML, Vel, Area</td>
<td>90x2</td>
<td>10</td>
<td>GC</td>
<td>GC higher with increased duration, mVel most reliable (0.64-0.95) EO/EC.</td>
</tr>
<tr>
<td>Harringe et al. [130]</td>
<td>BP, EO/EC F/C, normal stance</td>
<td>Path length, SD AP/ML, RMS vel AP/ML/total, area</td>
<td>120</td>
<td>2</td>
<td>ICC2.1</td>
<td>MMDC, CV</td>
</tr>
<tr>
<td>Bauer et al. [106]</td>
<td>BP, EC/EO/F, narrow stance</td>
<td>Mean area, length, sway</td>
<td>30</td>
<td>3</td>
<td>ICC2.1</td>
<td>All parameters ICC &gt;0.75 except area EC (0.71)</td>
</tr>
<tr>
<td>Demura et al. [131]</td>
<td>BP, EO/F, narrow stance</td>
<td>36 parameters (e.g. RMS, area, mVel, RMS Vel)</td>
<td>60</td>
<td>3</td>
<td>ICC (unclear)</td>
<td>All parameters ICC &gt;0.75 (e.g. mVel A: 0.96, B: 0.96, area A: 0.95, B: 0.92)</td>
</tr>
<tr>
<td>Doyle et al. [132]</td>
<td>BP EO/EC/F, normal stance</td>
<td>DC AP/ML/ short term/long term</td>
<td>30, 60, 90</td>
<td>10x2</td>
<td>GC</td>
<td>All parameters GC ≥0.70 after 2 trials 30sec.</td>
</tr>
<tr>
<td>Haidan et al. [133]</td>
<td>BP, EC/EO F/C, narrow stance</td>
<td>SD vel. ampl., phase plane,</td>
<td>30</td>
<td>3</td>
<td>ICC2.3</td>
<td>mVel EC/C 0.89, EC/F 0.87, EO/F 0.80. Area EC/C 0.65, EC/F 0.74, EO/F 0.10</td>
</tr>
<tr>
<td>Lin et al. [134]</td>
<td>BP, EC/F, narrow stance</td>
<td>MPF, mVel, RMS, area, DFA exponent, Hurst exponent (H)</td>
<td>60</td>
<td>2x3</td>
<td>ICC (modified), SEM</td>
<td>Young: mVel, RMS, area, DFA: ICC ≥0.75 same day, only mVel ICC≥0.75 inter-day. Elderly: All parameters ICC &gt;0.75 same day</td>
</tr>
<tr>
<td>Pinsault et al. [135]</td>
<td>BP, EC/F, normal stance</td>
<td>Area, range, vel., Vmax AP/ML</td>
<td>30</td>
<td>10</td>
<td>ICC2.1</td>
<td>Vel, Vmax, vel AP, Vmax AP &gt;0.75 (one trial). All &gt;0.75 if 3 trials averaged.</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Authors</th>
<th>Conditions</th>
<th>Measures</th>
<th>Participants</th>
<th>Reliability</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santos et al. [136]</td>
<td>BP, EO/EC/F, narrow stance</td>
<td>FD, mean freq / vel / dist, RMS</td>
<td>60</td>
<td>2</td>
<td>GC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RMS dist: EO 0.43, EC 0.45, mVel EO 0.45, EC 0.36, range EO 0.52, EC 0.28, MPF EO 0.50, EC 0.44.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salavati et al. [137]</td>
<td>BP, EO/EC F/C, narrow stance</td>
<td>SD amplitude / velocity, phase plane AP/ML</td>
<td>30</td>
<td>3</td>
<td>ICC2,3 SEM, CV, MMDC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD ampl. AP/ML: EO 0.61-0.64, EC 0.44-0.60, SD Vel AP/ML: EO 0.50-0.77, EC 0.71-0.83, Area: EO 0.33, EC 0.64, mVel EO 0.84, EC 0.91.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


All values are mean (SD). Commonly accepted interpretations for reliability coefficients are <0.40=“poor”, 0.40-0.75= “fair to good”, >0.75= “excellent” reliability. CV values ≤0.33 are interpreted as acceptable [138].

**2.4.2.2. The statistical analysis**

As with the general experimental setups, an equally heterogeneous selection of statistics for describing the reliability was used, including the coefficient of variation (CV), generalizability coefficient (GC) as well as Pearson’s correlation coefficient (PCC). The most commonly applied statistic however, were the different forms of the intra-class correlation coefficient (ICC). While most used models described originally by Shrout and Fleiss [138], others again employed modified versions [134]. About 30% (6/22) of the studies using the ICC failed to state the exact model used. The corresponding authors of these studies were contacted in order to gather the missing information but only two replies [121, 134] were received. Where ICC models were reported, the two-way random effect model (ICC2.1) was employed most often (Table 2.3).
Table 2.3.: Distribution of various interclass correlation coefficient models

<table>
<thead>
<tr>
<th>ICC model</th>
<th>1,1</th>
<th>2,1</th>
<th>2,3</th>
<th>3,1</th>
<th>3,4</th>
<th>3,k</th>
<th>modified</th>
<th>unclear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Studies</td>
<td>[118]</td>
<td>[106, 108, 111, 126, 130, 135, 139]</td>
<td>[133, 137]</td>
<td>[118, 128]</td>
<td>[105]</td>
<td>[107, 121]</td>
<td>[122, 134]</td>
<td>[114, 117, 120, 124, 131]</td>
</tr>
</tbody>
</table>

ICC: intra-class correlation coefficient

Two studies [132, 136] applied the related generalizability theory but described different “facets” for error calculation of the GC.

2.4.2.3. Relationships between methods and reliability

While various studies have investigated the same COP parameters such as mean velocity or area of sway, an inter-study comparison of each parameter’s individual reliability is often problematic because of differences in study designs. Table 2.4a shows the results of the COP parameter mean velocity (mVel) throughout various studies. Some results appear consistent but a comparison of this parameter’s reliability is difficult as the number of participants, the subjects’ health status or age may vary greatly between the studies. For example, the data by Benvenuti et al. [107] describes a cross-section of thirty-six participants with normal, moderate or severe levels of disequilibrium (age 74.5 years, open and closed eyes) on firm and compliant surfaces whereas Lafond et al. [126] tested only seven healthy elderly people (age 67.9 years, open eyes) on the firm surface of two force platforms. The results by Pinsault et al. [135] (ICC2,1 0.82-0.89) on the other hand were derived from ten young healthy adults (age 24.6 years) that were tested with closed eyes only.

While various studies have investigated the same COP parameters such as mean velocity or area of sway, an inter-study comparison of each parameter’s individual reliability is often
problematic because of differences in study designs. Only a few studies offer similar experimental procedures that allow for comparing the effect of various factors on the reliability of COP measures (Table 2.4 a-e).

Table 2.4a: Visual Condition

<table>
<thead>
<tr>
<th>Visual condition</th>
<th>Sampling frequency (Hz)</th>
<th>Cut-off frequency</th>
<th>Parameter</th>
<th>Number of trials</th>
<th>Duration (sec)</th>
<th>Result</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes open (EO)</td>
<td>100</td>
<td>5</td>
<td>Mean velocity</td>
<td>3</td>
<td>30</td>
<td>GC 0.83</td>
<td>[129]</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>10</td>
<td>Mean velocity</td>
<td>3</td>
<td>30</td>
<td>ICC2.1 0.89-0.95</td>
<td>[126]</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>10</td>
<td>Mean velocity</td>
<td>3</td>
<td>30</td>
<td>ICC2.3 0.80</td>
<td>[133]</td>
</tr>
<tr>
<td>Eyes closed (EC)</td>
<td>64</td>
<td>unclear</td>
<td>Mean velocity</td>
<td>3</td>
<td>30</td>
<td>ICC2.1 0.84</td>
<td>[135]</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5</td>
<td>Mean velocity</td>
<td>3</td>
<td>30</td>
<td>GC 0.84</td>
<td>[129]</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>10</td>
<td>Mean velocity</td>
<td>3</td>
<td>30</td>
<td>ICC2.3 0.87</td>
<td>[133]</td>
</tr>
</tbody>
</table>

ICC: intra-class correlation coefficient
Commonly accepted interpretations of ICC and GC are: <0.40=“poor”, 0.40-0.75= “fair to good”, >0.75= “excellent” reliability [138].

Table 2.4b: Sampling duration

<table>
<thead>
<tr>
<th>Duration (sec)</th>
<th>Sampling frequency (Hz)</th>
<th>Cut-off frequency (Hz)</th>
<th>Root Mean Square (RMS) AP/ML</th>
<th>Mean Velocity</th>
<th>Area (A)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>20</td>
<td>10</td>
<td>EO/F ICC2.1 0.35-0.39</td>
<td>EO/F ICC2.1 0.73-0.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>5</td>
<td>EO/F ICC3.k 0.32-0.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5</td>
<td>clear</td>
<td>EO/F GC 0.64-0.93</td>
<td>EC/F GC 0.45-0.83</td>
<td>[129]</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>10</td>
<td>clear</td>
<td>EO/F ICC2.3 0.80</td>
<td>EC/F ICC2.3 0.74</td>
<td>[133]</td>
</tr>
<tr>
<td>60</td>
<td>20</td>
<td>10</td>
<td>EO/F ICC2.1 0.52-0.61</td>
<td>EO/F ICC2.1 0.77-0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>5</td>
<td>EO/F ICC3.k 0.53-0.65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>unclear</td>
<td>EO/F PCC 0.28-0.69</td>
<td>EO/F PCC 0.85-0.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5</td>
<td>clear</td>
<td>EO/F GC 0.69-0.94</td>
<td>EC/F GC 0.52-0.88</td>
<td>[129]</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>10</td>
<td>EO/F ICC2.1 0.46-0.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5</td>
<td>clear</td>
<td>EO/F ICC2.1 0.56-0.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>100</td>
<td>5</td>
<td>EO/F GC 0.68-0.95</td>
<td>EO/F GC 0.55-0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>20</td>
<td>10</td>
<td>EO/F ICC2.1 0.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>5</td>
<td>EO/F ICC3.k 0.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>10</td>
<td>EO/F ICC2.1 0.68-0.74</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Commonly accepted interpretations of ICC and GC are: <0.40=“poor”, 0.40-0.75= “fair to good”, >0.75= “excellent” reliability [138].
### Table 2.4c: Number of repetitions

<table>
<thead>
<tr>
<th>Study</th>
<th>Sampling frequency (Hz)</th>
<th>Cut-off frequency</th>
<th>Condition</th>
<th>Duration (sec)</th>
<th>Results &lt;3 repetitions</th>
<th>3-5 repetitions</th>
<th>6-10 repetitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>[135]</td>
<td>64</td>
<td>unclear</td>
<td>EC/F (mVel)</td>
<td>30</td>
<td>ICC 2.1 0.82-0.83</td>
<td>ICC 2.1 0.82-0.88</td>
<td>ICC 2.1 0.88-0.89</td>
</tr>
<tr>
<td>[129]</td>
<td>100</td>
<td>5</td>
<td>EC/F (mVel)</td>
<td>30</td>
<td>GC 0.64-0.79</td>
<td>GC 0.84-0.89</td>
<td>GC 0.91-0.94</td>
</tr>
<tr>
<td>[133]</td>
<td>200</td>
<td>10</td>
<td>EC/F (mVel)</td>
<td>30</td>
<td>ICC 2.3 0.87</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EC: eyes closed, EO: eyes open, F: firm surface, GC: G-coefficient, ICC: intra-class correlation coefficient, mVel: mean velocity.

Commonly accepted interpretations of ICC and GC are <0.40 = poor, 0.40-0.75 = fair to good, >0.75 = excellent reliability [138].

### Table 2.4d: Stance

<table>
<thead>
<tr>
<th>Study</th>
<th>Sampling frequency (Hz)</th>
<th>Cut-off frequency</th>
<th>COP parameter</th>
<th>Duration</th>
<th>Number of trials</th>
<th>Condition</th>
<th>Results Normal stance</th>
<th>Results Narrow stance</th>
</tr>
</thead>
<tbody>
<tr>
<td>[122]</td>
<td>20</td>
<td>5</td>
<td>RMS</td>
<td>30</td>
<td>1</td>
<td>EO/F</td>
<td>ICC 0.35-0.39</td>
<td>ICC 0.32-0.58</td>
</tr>
<tr>
<td>[136]</td>
<td>100</td>
<td>10</td>
<td>AP/ML</td>
<td>60</td>
<td>7</td>
<td>EO/F</td>
<td>ICC 0.96</td>
<td>ICC 0.75</td>
</tr>
<tr>
<td>[111]</td>
<td>100</td>
<td>unclear</td>
<td>mVel</td>
<td>25</td>
<td>9</td>
<td>EO/F</td>
<td>ICC2.1 0.55</td>
<td>ICC2.1 0.27</td>
</tr>
</tbody>
</table>

EC: eyes closed, EO: eyes open, F: firm surface, GC: G-coefficient, ICC: intra-class correlation coefficient, mVel: mean velocity.

Commonly accepted interpretations of ICC and GC are <0.40 = poor, 0.40-0.75 = fair to good, >0.75 = excellent reliability [138].

### Table 2.4e: Age

<table>
<thead>
<tr>
<th>Age group</th>
<th>Age</th>
<th>Sampling frequency (Hz)</th>
<th>Cut-off frequency</th>
<th>COP parameter</th>
<th>Condition (duration)</th>
<th>Number of trials</th>
<th>Result</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-30</td>
<td>19.9yrs</td>
<td>100</td>
<td>5</td>
<td>Mean Velocity</td>
<td>EO/F (60sec)</td>
<td>7</td>
<td>GC 0.93</td>
<td>[129]</td>
</tr>
<tr>
<td></td>
<td>26.9ys</td>
<td>100</td>
<td>10</td>
<td>Mean Velocity</td>
<td>EO/F (60sec)</td>
<td>7</td>
<td>GC 0.75</td>
<td>[136]</td>
</tr>
<tr>
<td></td>
<td>20.4yrs</td>
<td>20</td>
<td>unclear</td>
<td>Mean Velocity</td>
<td>EO/F (60sec)</td>
<td>2</td>
<td>ICC 0.94-0.96</td>
<td>[131]</td>
</tr>
<tr>
<td>60-80</td>
<td>67.9yrs</td>
<td>20</td>
<td>10</td>
<td>Mean Velocity</td>
<td>EO/F (60sec)</td>
<td>7</td>
<td>ICC 2.1 0.96</td>
<td>[126]</td>
</tr>
<tr>
<td></td>
<td>72.9yrs</td>
<td>20</td>
<td>unclear</td>
<td>Mean Velocity</td>
<td>EO/F (60sec)</td>
<td>2</td>
<td>ICC 7 0.96</td>
<td>[131]</td>
</tr>
</tbody>
</table>


Commonly accepted interpretations of ICC and GC are <0.40 = poor, 0.40-0.75 = fair to good, >0.75 = excellent reliability [138].

To allow a general overview, Table 2.5. lists experimental setups that have shown to yield reliable COP data throughout the different studies.
Table 2.5. Setups reported to provide reliable COP data

<table>
<thead>
<tr>
<th>Setup</th>
<th>Considered most reliable number of studies (%)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vision</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyes open</td>
<td>4 (15%)</td>
<td>[114], [116], [117], [118]</td>
</tr>
<tr>
<td>Eyes closed</td>
<td>11 (85%)</td>
<td>[105], [108], [119], [120], [32], [122], [126], [129, 130], [133]</td>
</tr>
<tr>
<td>**Duration (sec) *</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60-89</td>
<td>2 (23%)</td>
<td>[105], [137]</td>
</tr>
<tr>
<td>90-120</td>
<td>4 (67%)</td>
<td>[121], [125], [126], [129]</td>
</tr>
<tr>
<td><strong>Surface</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compliant</td>
<td>1 (20%)</td>
<td>[106]</td>
</tr>
<tr>
<td>Firm</td>
<td>4 (80%)</td>
<td>[108], [107], [129], [133]</td>
</tr>
<tr>
<td><strong>Repetition †</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;3</td>
<td>1 (20%)</td>
<td>[122]</td>
</tr>
<tr>
<td>3-5</td>
<td>4 (60%)</td>
<td>[136], [131], [132]</td>
</tr>
<tr>
<td>5-10</td>
<td>1 (20%)</td>
<td>[116], [126]</td>
</tr>
<tr>
<td><strong>Stance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>1 (100%)</td>
<td>[111]</td>
</tr>
</tbody>
</table>

Numbers do not always add up to 100 due to rounding.

* Only studies investigating multiple time intervals of up to 60 sec are included
† Only studies investigating the effect of at least 3 trials are included
§ Only studies comparing both stances are included

2.5. Discussion

2.5.1. General considerations

Due to the heterogeneous study designs and statistical models used there remains little common ground for combining the reliability of all data presented. Only a few papers allowed for direct inter-study comparison of results and most of the conclusions had to be drawn from those studies. No quantitative pooling of results from the studies was possible, but we were nevertheless able to extract enough qualitative information to make recommendations regarding reliable experimental setups for COP measurements.

Many trials on the reliability of COP measures were conducted as a complementary part of papers concerned with postural control and as such COP did not appear in the title or keyword
lists. Our search strategy addressed this problem by using hand searches of reference lists of key papers and this identified some of the included papers.

With regards to differences between within-day and between-day reliabilities, it has been shown that trials run on the same day yield higher values [107, 134]. While intra-trial and inter-trial reliability needs to be discussed, inter-rater reliability is unlikely to be of concern due to the simplicity of the apparatus, task and instructions. It appears, however, that it was this simplicity that has led to a lack of standardization in operation.

When considering potential sources of variability affecting the reliability of COP measures one may distinguish between effects of the measurement procedures themselves that can be controlled (e.g. sampling duration, signal processing) and sources of variability that may not (e.g. joint/muscle function). Generally, the intra-subject variability may be at least partially explained by the learning effect observed [109], leading to an optimization of energy expenditure by progressively reducing body sway over the course of repetitions [140].

2.5.2. Choice of statistics

The choice of different statistics (e.g. ICC, GC, PCC) has a profound effect on the reliability results of identical data sets - with subsequent consequences for interpretation. The most commonly applied statistical tests were different models of the intra-class correlation coefficient (ICC) [138] and the coefficient of variation (CV). Two studies [113, 115] employed Pearson’s correlation coefficients (r) although its application in test-retest reliability studies is often discouraged because of its inability to detect systematic error [139].
There are numerous versions of the ICC described in the literature (plus additional modified versions), six of these were employed in the presented studies. The ICC is a ratio of variance deriving from ANOVA that is unitless and theoretically varies between 0.0 and 1.0. There has been some debate about where to set clinically acceptable correlation levels [141]. For the purpose of this review, the authors used the definition stated in the classic Shrout and Fleiss [138] paper, regarding an ICC≥0.75 as indicative of good reliability.

The issue with the described heterogeneity of chosen ICC models (Table 2.3) is that, depending on the data, different models are likely to yield varying results [139]. This (in conjunction with the heterogeneous experimental setups) renders a broader direct comparison of results even more difficult.

Seven studies did not specify the ICC model used. The corresponding authors were contacted, five failed to provide the requested information. Consequently, their results are impossible to compare. The ICC type selected most often was the 2-way random effects model (ICC$_{2,1}$) where the raters are considered a random effect and both systematic and random error are considered. It is normally the model of choice for comparing retest-reliability between different measuring devices. However, the use of ICC$_{2,1}$ has been criticized for retesting on single items of equipment as the resulting reliability may be degraded by a variable learning effect (depending on the number of trials) and not by constant differences in values arising between the devices [142]. When interpreting results from studies that chose model 3 ICCs [105, 107, 118, 128] it should be noted that only random errors are considered while systematic errors are disregarded. This also accounts for Pearson’s correlation coefficients [143].

As it will be seen later on in the discussion, the magnitude of the ICC is dependent on the variability of the COP data. The heterogeneity of the participants therefore needs to be
carefully considered, as high ICC values may mask poor test-retest consistency if there is a large variability between the participants (as would be expected e.g. in the elderly). Conversely, even in the presence of low inter-participant variability, small test-retest variations may cause low ICC values [139, 144]. It is therefore necessary to examine the standard error of measurement (SEM) in conjunction with the ICC values as the latter normalizes measurement error relative to the heterogeneity of the participants. This was utilized in some studies in this review [114, 134, 135, 137].

Table 5 shows that results of the related models ICC$_{2,1}$ and ICC$_{2,3}$ are very similar. This also accounts for many of the values derived from unknown ICC types, which suggests the application of the same statistics as the experimental setups are similar. It may be argued that despite the unknown ICCs, the different results allow at least a limited comparison of results. As the error term of the ANOVA reflects the interaction between trials and subjects, this error term is small if the subjects’ readings change in a similar fashion across a recording session. This would be expected as the baseline demographics of the participants in the studies are very similar. If the systematic error is small, ICC results derived from different statistics (e.g. 1-way and 2-way models) will be similar. This can be observed in Table 2.5b when comparing the values reported by Lafond et al. (ICC$_{2,1}$) [126] and Carpenter et al. (ICC$_{3,k}$) [121].

Recently, Doyle et al. [109, 129, 132] and Santos et al. [136] argued that an approach using the generalizability coefficient (GC) may be more appropriate in order to identify sources of variance. While Classical Test Theory merges the error component of the observed score into one undifferentiated term, generalizability theory attempts to investigate variances of this component by a series of (one-factorial) ANOVA procedures. For interpretation, GC is an analogue to the reliability coefficient of the classical test theory where GC≥0.75 is considered good to excellent. Although there is no indication that this might be the case with the studies reviewed, issues with GCs may arise from the fact that an author may artificially alter the
results by the choice of the so-called “facets” he deems relevant as sources of variance. As both authors included different “facets”, a direct comparison between their respective results is equally problematic as it is with different ICC models.

In conclusion, it needs to be kept in mind that while the differences resulting from the different statistics may be marginal under the described conditions, only studies employing the same formulas (GC or ICC) can be directly compared with confidence. Results derived from similar or identical experimental setups may nevertheless offer a limited comparability. Generally, trends like higher reliability with increasing trial numbers or under visual deprivation are present irrespective of the ICC model used, the overall conclusions therefore remain unaffected.

2.5.3. Subject demographics and morphology

Together with subject morphology, joint and muscle function are the main biomechanical factors involved in balance control [145]. All but one of the studies reviewed relied on self-reported health information from the subjects without conducting some form of physical examination prior to the study. It remains questionable whether the participants in all cases remembered to report relevant previous injuries. In addition, functional impairment affecting the study outcome may go completely undetected by the presumably healthy individual as long as no interference with daily activities is noticed. Due to the generally low number of participants throughout the studies, such factors may become statistically relevant. Not counting the large scale study by Kitabayashi et al. [124], the average number of participants drops to about twenty-two. Best practice would suggest conducting a thorough physical examination to identify underlying physical problems that may influence the readings.
While most articles provided basic details on the baseline demographics, only a few articles addressed the effect of intrinsic physical differences between subjects such as body mass index (BMI), height or weight on the reliability of COP measures [137, 146]. This should be included in all COP studies as it has been demonstrated that selected temporal-distance COP parameters such as mean velocity or range are strongly dependent on the subject’s height [146] and weight [147].

As the correlation between height and reliability increases under EC condition, it has been argued that with loss of visual afferent input the effect of inertial properties of the body on postural sway become predominant [147]. A linear increase of COP velocity with increasing body weight, accounting for more than 50% of the observed variance, has also been demonstrated. As with increasing BMI (obesity) the centre of mass is located more anteriorly of the base of support and the foot mechanoreceptor afferents may be de-sensitized [147], the resulting postural instability may affect the reliability of COP measures. However, another study argued that these effects are minimal when averaging at least three trials [137], we nevertheless suggest normalizing the acquired data to the described factors until further evidence is established. Normalizing refers to statistically removing the dependence of stabilometric parameters on biomechanical factors [145]. Originally proposed by O’Malley, it involves then removal of linear trends and has the advantage of retaining the original units. During the normalization process, the estimated regression model is subtracted from the parameters’ original values. In the next step, the mean value of the original data is added, in order to keep the data in the same range. This way, the quality of the data and resulting conclusions may be enhanced.
2.5.4. Age and gender

As only four studies offer direct comparability, it is difficult to reach a firm conclusion regarding the effect of age and gender on the reliability of COP measures. Most studies enrolled mixed-gender groups which have shown high correlation coefficients [105]. In addition, even though it has been shown that COP measures differ between age groups [12, 105, 148], the reliability of these measures is not influenced by gender.

Demura et al. showed excellent reliability for a selection of different COP measures in both young and elderly subjects [148]. Lin et al., however, found higher inter-class correlation coefficients in groups of healthy elderly participants [134]. Many factors may influence these coefficients. Low values for example may be either caused by large inter-session or small inter-subject variances [144]. The higher ICCs reported in the elderly may therefore be at least partially attributed to a higher variability of measures due to the expected age-related deficits in vision, proprioception or muscle strength.

The possible effect of fatigue, especially in a population of balance affected elderly subjects, has to be considered when increasing the trial number or duration on a single day. In the elderly finding the best ratio between trial duration and number of repetitions is of special interest.

2.5.5. COP parameters

Recent studies suggest that the COP time series may represent the dynamics of a nonlinear (chaotic) system [149] that may be characterized using fractal dimension [12, 108, 136] and Stabilogram Diffusion Analysis (SDA) [127, 128]. Fractal dimension provides an indication of a
signal's complexity by analyzing it in its entirety and describing the shape. SDA assumes that COP can be modeled as a system of correlated, random walks, thereby addressing the dynamic nature of COP motion. Accordingly, its analysis is based on the random selection of two pairs of COP data [127]. It has been shown to successfully differentiate between COP pattern of healthy elderly and young individuals [12].

Doyle et al. [108] suggested that fractal analysis is a superior tool for COP investigations compared to using traditional COP parameters. This notion was based on their observations of low reliability coefficients for mean velocity (mVel) or sway area (ICC\textsubscript{2,1} 0.05-0.71) while fractal dimension showed high reliability (ICC\textsubscript{2,1} 0.62-0.90) in association with low coefficients of variation (CV\%) values (1.8-6.7). In a later study, Santos et al. [136] did not support this trend. Their results show that fractal dimension data sets have comparable reliability values to traditional measures. It is possible that the differences may be explained by the study design. Santos et al. used 60sec sampling duration, while Doyle et al. used only 10sec, which is surprising as previous research quoted in their own study [126] indicated that this is an insufficient time frame to gain reliable data. Amoud et al. [128] compared the reliability of SDA and Detrended Fluctuation analysis (DFA) over three time intervals (2.5, 2 and 10sec) and showed that only AP motion of elderly subjects at 10sec duration could be assessed with a satisfactory reliability (ICC\textsubscript{3,1}≥0.75). Limitations of their study include that no instructions regarding the foot placement were given as well as the short sampling durations. As it will be shown later on, longer durations may have yielded higher reliability coefficients. For more details on SDA and DFA refer to Deligniéres et al. [150]. The importance of sampling duration will be discussed below.

Traditional parameters that employ minimal, maximal or peak-to-peak readings such as maximal amplitude should be avoided as they use only one or two data points among the entire recorded data and are therefore subject to great variances with subsequent low
reliability. As averaging data may reduce the statistic effect of individual extreme readings, COP summary measures such as COP mean velocity should be used instead. Considering the low number of participants throughout the available studies, extreme values may influence these means - as the great spectrum of some confidence intervals suggest.

The data available shows that mean velocity (mVel) is one of the most commonly used COP parameters. While the limitations described earlier have to be considered, it never the less shows consistently acceptable overall reliability values (Table 2.5) and can be considered the most reliable traditional COP parameter. While root mean square (RMS), sway area, path length in antero-posterior and medio-lateral (AP/ML) direction as well as range and other summary measures are among the most often used parameters, we found that their reported reliability varies more and may therefore be used with more caution.

Due to the heterogeneity in study design, no papers with similar enough setups could be identified to allow for a broader comparison of individual COP parameters. The overall results, however, suggest that with sufficient repetitions and sampling duration, all COP parameters should gain acceptable reliability ($r \geq 0.75$). It has to be kept in mind though that this also depends on the technical suitability of the forceplate.

2.5.6. Experimental Setup

About 65% (9/14) of the studies reviewed failed to state the instructions given to participants for the experiment. The two most commonly used instructions in the studies reviewed were “stand quietly” and “stand as still as possible”. In their study, Zok et al. [151] showed that the instructions issued to the participants during posturography may have a significant impact on the results, potentially affecting the reliability. With one exception, all COP parameters
investigated showed variations of 8% to 71% depending on which one of the instructions was
given. The mean velocity, which was the most commonly used parameter in this review
(12/74, 16%), showed variations of around 10%. The results obtained when the subjects were
asked to “stand as still as possible” showed tighter confidence intervals indicating a higher
consistency. We therefore recommend explicit instructions be given to participants in COP
measurement studies. These instructions should be “stand as still as possible” while looking
straight ahead.

Only two studies reported some form of standardization of the environment such as lighting,
temperature or daytime for the follow-ups [106, 125]. Another general limitation is the fact that
40% of the studies reviewed did not specifically state whether shoes and socks were removed
or not. While it can be assumed that at least shoes were taken off in most unclear cases,
socks may alter sensory input and thereby affect the study results. This is particularly true in
older subjects where decreased peripheral proprioception would be expected. Another
limitation were potentially varying foot positions when stepping off and back on the force
platform during brakes. Only one study avoided this effect by having the participants sit down
during breaks while maintaining the original foot position [124]. The arms at sides position was
most commonly used position (60%). From a biomechanical point of view, this is more likely to
keep the COP in a natural position than a position with hands in front or on the back.
Accordingly, we recommend bare feet and arms at sides when data is being recorded. We
also recommend sitting with feet in their original position during breaks.

2.5.7. Sampling and cut-off frequency

It has been shown that COP measures and its reliabilities vary depending on both the
acquisition and cut-off frequency chosen [123, 127]. On a simple basis, the sampling
frequency determines how closely and exact the COP excursions are measured. A too low frequency might lead to a significant data loss by "missing" sway path (Figure 2.2).

**Figure 2.2:** The effect of sampling frequency on recording COP\(_{net}\) data in AP/ML direction

In the literature, sampling frequencies ranging from 10-200Hz have been reported [106, 111, 122, 126, 129, 130, 132, 133, 135, 136] and the question is whether the reported variations in COP reliability across similar experimental setups are at least partially due to the different frequencies chosen.

Filtering of any signal is aimed at the selective rejection, or attenuation, of certain frequencies. If the sampling frequency is chosen too low, the loss of intermediate points will affect the recorded COP trajectory. As the concept of the SDA is based on the random use of pairs of COP data, the effect of sample frequency remains unclear as no effect could be demonstrated [127]. The effect on parameters on the basis of frequency distribution of data such as mean
power frequency, however, is marked, whereas measures of mean displacement such as mean velocity or mean amplitude are far less sensitive to different sampling frequencies [123]. It has been shown that COP mean velocity displacement and path length were 26.1% greater when sampling frequencies of 50Hz were used compared to 10Hz [127] which would be expected with more data points, describing the shape of the COP path more accurately. This however, did not significantly affect reliability as mean velocity showed generally consistent reliabilities ($r=0.82-0.89$) across different frequencies ranging from 64-200Hz [129, 133, 135] (Table 2.5).

In COP measurements, a low-pass Butterworth-type filter passes the lower frequency signals unattenuated, while at the same time attenuating the higher frequency background noise. A compromise has to be made in the selection of this frequency. If the cut-off frequency is chosen too low, the noise is reduced significantly, but at the expense of an increased signal distortion. On the other hand, the occurring distortion is reduced, but too much noise is allowed to pass if the cut-off frequency is set too high [43]. In addition to attenuating the signal, there is a phase shift of the output signal relative to the input. To counter this, a zero-phase-shift filter may be applied to cancel out the phase lag by filtering the once-filtered data again in the reverse direction of time thereby introducing an equal and opposite phase lead so that the net phase shift is zero [128].

Depending on the parameter selected, the choice of the cut-off frequencies has a significant effect on the reliability of COP data. The results for mean velocity for example showed low variation from ICC$_{2,1}$ 0.75 at 0.8Hz to 0.71 at 10Hz, while the reliability values of mean power frequency dropped from 0.21 to 0.13 under the same condition [123]. In the literature, a cut-off frequency of 10Hz has been suggested as the best compromise to reject noise power [123].
Depending on the COP parameter chosen, care should be taken with regards to the sampling frequency. Although further research is necessary, a sampling frequency of 100Hz with a cut-off level of 10Hz appears advisable for traditional COP measures.

2.5.8. Sampling duration

The test-retest results suggest that the number of trial recordings and duration appears to be a critical factor for obtaining reliable data sets. However, there have been only a few attempts to provide recommendations on both the length and number of trials that should be used when assessing balance. While earlier studies suggest that reliable data may be obtained with sample durations of 10 to 60sec [110, 112, 113, 123], this has later been disputed. Studies investigating multiple time intervals of up to 120sec concluded that between 90 and 120sec are necessary to reach correlation coefficients of ≥0.75 for most COP parameters with confidence [121, 126, 129]. Lengthening trial duration further once an acceptable level of reliability is reached did not significantly reduce variability [106]. While fatigue with prolonged trial duration may be an issue in measurement variability, the use of 90-120sec recordings is unlikely to be of concern even when working with elderly subjects. A limitation may be that some studies tested individual time intervals while others sampled different durations from one continuous reading. However, on balance we recommend the 90-120 second time frame.

When similar studies are compared, the results confirm a trend towards increased reliability values with longer sampling durations (i.e. see Table 2.5). While the data presented includes only a limited selection of parameters from a few studies and from different statistical models, the values for mVel and RMS (AP/ML) show a positive relationship between sampling duration and reliability coefficient. This is also true for COP area, although the results for the different time intervals show a greater variation between the studies. In this case, similar results can be
observed with similar ICC models. The overall data indicates that a sampling duration of 90sec can be expected to yield acceptable reliability for all traditional COP parameters, whereas shorter durations for data derived from DFA may be sufficient.

2.5.9. Number of repetitions

In addition to trial duration, the number of repetitions to gain acceptable reliability (r≥0.75) also varies with the COP parameter under investigation and conflicting results have been reported. For COP mean velocity for example, just two 120sec trials are supposed to reach an ICC\textsubscript{2,1} >0.90, whereas COP range and RMS need four 120sec trials [126]. Furthermore, it has been stated that averaging two [124], three [137], four [129] or seven [136] trials yields acceptable reliability for the majority of COP parameters. Further lengthening trial duration once an acceptable level of reliability is reached did not significantly reduce variability [106]. With regards to differences between within-day and between-day reliabilities, it has been shown that trials run on the same day yield higher values [107, 134].

When comparing results of similar setups, the trend for increased trial numbers to yield more reliable data is apparent (Table 2.5). In a clinical setting, however, it may be argued that setups involving 10 trials in elderly people are impractical due to potential fatigue effects. Irrespective of the heterogeneous study designs in this review we conclude that averaging 3-5 trials of sufficient duration over one day is appropriate under most conditions.
2.5.10. Visual condition

Loss of vision does not affect COP measures of a young population during quite standing, while the effect is more marked in the elderly [152]. Under eyes closed conditions the reliability is lower for short sampling durations and rises as the individual adapts [112], leading to higher overall reliability values under eyes closed condition compared to eyes open [105, 106, 108, 119, 120, 122, 126, 129, 130, 136].

It has also been shown that while both conditions showed high reliability values, the overall eyes closed data was more reliable than eyes open even in elderly subjects [106]. This appears a bit surprising as postural stability in the eyes closed position would be expected to be harder to maintain due to the reduced effectiveness of peripheral proprioception with increasing age. While loss of vision leads to increased muscle stiffness [153], the higher variances of measures caused by the decreased postural stability under this visual condition may lead to higher ICC values, as described earlier. In addition, the trend by recent papers to report higher reliability estimates under eyes closed conditions may at least partially be attributed to improved technical equipment or more rigorous scientific procedures in conducting the studies. For best practice we recommend to conduct the data collection under eyes closed condition where practical.

2.5.11. Foot position

When no specific instructions are given, there is a great variability in the position of feet chosen by individuals during normal stance [154]. It has been shown that widening of the foot position increases the passive stability of the musculoskeletal system and decreases active neural control [146, 155]. A wide stance acts to strengthen the coupling between hips and
ankles and would be expected to yield higher reliability coefficients under eyes closed conditions (especially in the elderly). The proprioceptive sensitivity to lateral motion increases with larger base of support [156], in addition, the biomechanical coupling reduces the importance of vision.

As described in Chapter 1, the term “base of support” (BOS) in general terms refers to the space demarcated by the big toe distance (d₁) inter-malleolar distance (d₂) and the foot length (L) (Figure 2.3). In contrast, equally acceptable reliability values for eyes open and eyes closed trials in narrow stance have been reported in a group of healthy elderly subjects (78.7±3yrs) [106]. One explanation might be the previously described statistical effect of large inter-session variances due to decreased postural stability on the ICC.

Figure 2.3: Base of support

Illustration: Alexander Ruhe

Only one study by Hill et al. [111] directly compared narrow and normal stance. It showed that narrow stance measurements lead to lower overall reliability than feet apart (ICC\(_{2,1}\) 0.27 compared to 0.55). The sampling duration, however, was short (25sec). Comparing selected data of similar studies indicates that seven repetitions of 60sec duration yield acceptable reliability for both narrow foot position (GC 0.75) and normal stance (GC 0.96), although the latter showed higher values [136]. When data from 30sec after a single trial are compared, narrow stance also reached higher values than a normal feet position [122] (Table 2.5).

No conclusion regarding the more reliable foot position can be reached with the current data available; therefore best practice suggests to use both stances in each trial until further research is conducted.

2.5.12. Surface condition

Three studies investigated data obtained from both firm (F) and compliant surfaces (C). All of them enrolled subjects with various conditions ranging from vestibular impairment [115] and LBP to lower limb injuries [130, 132]. Without testing with open eyes, Salavati et al. [137] reported lower ICC\(_{2,3}\) values with comparatively high standard error of measurement and coefficient of variation values for trials run on compliant surfaces with closed eyes. Harriage et al. [130] also found generally lower correlation coefficients (ICC\(_{2,1}\)) during eyes closed and eyes open trials for both 60 and 120sec sampling duration. Benvenuti et al. [107] agree with this trend but add that the parameter COP antero-posterior distance tested on a compliant surface may be as reliable as on a firm base. This was the only study using elderly subjects (74.5 years), while the others enrolled young participants (14.9-38.4 years).
Even considering the differences in patient demographics and health condition, it may be concluded that data obtained on a firm surface is more reliable, although no similar setups allow for a specific inter-study comparison of results. This review recommends using a firm surface although further research is required.

2.6. Conclusion

The overall results indicate that traditional parameters show acceptable reliability if our recommendations are considered in the study design. The test-retest reliability appears to depend primarily on factors such as the number of trial recordings and duration rather than the selection of COP parameters itself. Care should be taken to assess the subject’s physical status and properties prior to the measurements. The primary finding of this systematic review is there has been relatively little consistency in the methodology employed and measurements selected for COP analysis when using a force-platform.

We recommend the following methods should be employed: Regarding the data acquisition duration, the results suggest that a minimum of 90sec is required to reach acceptable reliability for all traditional COP parameters in healthy subjects. A sampling frequency of 100Hz with a cut-off frequency of 10Hz is advisable. In addition, measurements should be conducted under eyes closed condition on a firm surface where practical. Averaging the results of three to five repetitions can be expected to yield reliable data. Although the specific effect on the reliability remains unclear, the current evidence suggests that “stand as still as possible” should be the instruction issued prior to the recording. No final recommendation regarding the foot position is possible at this point (Table 2.6).
Table 2.6: Recommendations for optimal reliability

<table>
<thead>
<tr>
<th>Factor</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of data acquisition</td>
<td>Minimum 90 sec</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>100Hz</td>
</tr>
<tr>
<td>Cut-off frequency</td>
<td>10Hz</td>
</tr>
<tr>
<td>Visual condition</td>
<td>Eyes closed</td>
</tr>
<tr>
<td>Surface condition</td>
<td>Firm</td>
</tr>
<tr>
<td>Number of trials</td>
<td>3-5</td>
</tr>
<tr>
<td>Instructions given</td>
<td>&quot;stand as still as possible&quot;</td>
</tr>
</tbody>
</table>

In order to allow for inter-study comparison of COP results, there is need for a generally agreed form of standardization of measurement procedures. We believe that this review may aid in this process.

2.7. Limitations

This review has potential limitations including the search strategy. Many trials on the reliability of COP measures were conducted as a complementary part of studies concerned with postural control and did not necessarily appear in the titles or keywords. As a result, online database searches were often inadequate in locating all articles that met the inclusion criteria. A dynamic search strategy was employed to address that problem; in addition, selected hand searches of reference lists were necessary to identify many of the relevant papers. Another limitation is fact that only a few papers allowed for direct inter-study comparison of results and most of the conclusions had to be drawn from those studies. No quantitative pooling of results from the studies was possible. The review was therefore conducted on a qualitative basis.
CENTER OF PRESSURE EXCURSIONS AS A MEASURE OF BALANCE PERFORMANCE DURING STATIC TASKS CONDITIONS IN PATIENTS WITH NON-SPECIFIC LOW BACK PAIN COMPARED TO HEALTHY CONTROLS - A SYSTEMATIC REVIEW OF THE LITERATURE

CHAPTER 3

Center of pressure excursions as a measure of balance performance during bipedal static tasks conditions in patients with non-specific low back pain compared to healthy controls

3.1. Background

Having explored the factors associated with the reliability of COP measures in the previous chapter offers a better appreciation of postural sway results. As this thesis will discuss the effect of pain in neck, mid-back or low back on postural sway, the available literature was reviewed for previous studies investigating this topic. Unfortunately, no research specific to mid-back pain and COP excursions was identified. Consequently, only studies concerning low back and neck pain are presented in this and the following chapter.

Low back pain is a common condition with a reported 1-year prevalence ranging from 22% to 65% [157]. While the majority of these cases resolve within six weeks without medical intervention [158], a minority of around 20% may progress to become chronic and constitute the western world’s most prevalent and costly health problem [159]. Recent evidence showed that while age is a major determinant for balance, low back pain may account for up to 9% of the variance in balance [160].

A variety of theories exist about the potential effect of non-specific low back pain (NSLBP) on postural sway. Ideally, the body should be able to generate quick COP transitions that just
exceed the current position of the center of mass (COM) [8] and accelerate it into the opposite direction in order to maintain balance.

Muscle nociceptive input may be accompanied by severe reduction of position sense of the hand and by loss of stimulus perception [161], which points toward a pain-induced depression of pre- or postsynaptic inhibition of premotor neurons intercalated in spinal proprioceptive pathways [162]. This may interfere with the feed-forward mechanism of postural control described earlier, leading to a delayed muscle recruitment in response to COM perturbations [68].

On a basic level, it has also been proposed that (chronic) damage of sensory tissues in the lumbar spine, trunk [163] or lower extremities [164] may affect postural stability in a similar way. Deterioration of this proprioceptive information from these areas may be the determining factor in reducing the accuracy in the sensory integration process as described in Chapter 1. The resulting imprecise estimation of the COM position especially in chronic LBP sufferers may then lead to an increase in the safety margin of the adaptive COP shifts with regard to the predicted COM oscillations [61].

Another possible mechanism behind balance alterations is acute "pain interference" as described by Crombez et al. [165]. In this case, discharge from high-threshold nociceptive afferents interferes with spinal motor-pathways [166] as well as the motor cortex [161]. In addition it has been shown that pain may cause an increased pre-synaptic inhibition of muscle afferents [167] as well as affecting the central modulation of proprioceptive spindles of muscles [168], causing prolonged latencies by the decrease in muscle spindle feedback. These alterations may lead to decreased muscle control and result in increased postural sway.
This literature review will attempt to identify possible differences in COP pattern between NSLBP sufferers and healthy controls that may relate to the mechanisms described above. This step is fundamental before investigating whether a connection between the magnitude of these differences and the LBP intensity or location exists.

To our knowledge no systematic review has been conducted to investigate the possible impact of low back pain on COP pattern and the possible association of this effect with pain intensity or disability.

The aims of this systematic literature review were 1) to determine if there are significant differences in COP pattern between LBP patients and healthy controls, 2) to investigate whether the magnitude of these COP excursions are related to the level of pain perception or 3) to the perceived level of disability.

3.2. Methods

3.2.1. Search strategy

A comprehensive search strategy was developed by identifying all potentially relevant search terms, categorizing these terms into specific search phases and subsequently combining them by using Boolean terms. This search strategy was applied to six different electronic databases: PubMed, MEDLINE, EMBASE, Web of Science, ScienceDirect, Digital Dissertations and the Cochrane library. The detailed search strategy will be made available upon contacting the corresponding author.
3.2.2. Electronic searches

All databases were searched using the search strategy described above. Appropriate minor modifications to the basic search template were made to optimize the strategy in each of the six databases. Papers were limited to human studies published between January 1980 and July 2009.

3.2.3. Searching other resources

The hand search included analyzing references cited in studies selected from the original online search. Citation searches of relevant studies were conducted using the PubMed, MEDLINE and ScienceDirect databases.

3.2.4. Selection Criteria

Papers were limited to peer-reviewed journals and dissertations without restrictions regarding language. Wide inclusion and exclusion criteria for study designs were in order to not overlook potentially relevant papers.

The inclusion criteria were: Papers in any language that were fully or partially concerned with COP measures of subjects with NSLBP derived from bipedal static tasks on a force plate, compared to measures of healthy controls. For the purpose of this review, NSLBP was broadly defined as pain in the low back region of musculoskeletal etiology in the absence of any neurological symptomatology or structural damage due to trauma or serious pathology such as cancer or infection.
All COP measures, experimental setups and statistical models fitting these criteria were considered. No limitations of the type of patient demographics applied. We excluded studies with insufficient documentation of patient demographics or experimental setup where this rendered data extraction impossible. In addition, papers that were anecdotal, speculative or editorial in nature or studies that employed some form of translation of the force platform were excluded.

3.2.5. Data extraction and management

For the purpose of this review AR acted as the principal reviewer. The colleague Tino Bos, DC (TB) was involved independently in the process of identifying relevant studies and did not participate in further analysis of the finally included papers. A third reviewer (AS) was used for a majority decision in case discrepancies between AR and TB were not reconciled by discussion. To standardize the procedure between the reviewers, the main author developed a detailed data extraction sheet to acquire general information on objectives, design, participant’s demographics and outcomes. This also facilitated critical appraisal where each study was individually analyzed. For procedure control a trial was conducted with two papers similar but unrelated to the review question and the results discussed. If any title and abstract did not provide enough information to decide whether or not the inclusion criteria were met, the article was included for the full text selection.

With regards to the research question, the data extraction consisted of five main areas regarding low back pain and disability: 1) location and origin of the pain, 2) LBP duration prior to the measurements, 3) number of previous painful episodes, 4) perceived pain intensity and 5) any reported disability level.
3.2.6. Assessment of methodology

Recently it has been suggested that combined quality scores should not be incorporated into systematic reviews and instead the accuracy should be assessed by an investigation into individual quality scores [169].

The reviewers specifically assessed the application, documentation and association of six individual items with regards to differences in COP measures between LBP patients and healthy controls: 1) subject demographics and morphology, 2) sample duration, 3) number of trial repetitions, 4) visual condition (eyes open or eyes closed), 5) stance, and 6) type of platform surface.

3.3. Results

3.3.1. Literature search results

Initially, the online search strategy identified 157 studies of which abstracts were screened individually by the reviewers. The application of inclusion/exclusion criteria and consensus by the reviewers on the titles and abstracts eliminated a further 119 papers. The most common reason for rejection was not meeting the selection criteria such as static or bipedal tasks. From the titles and abstracts of papers selected (n=38), full papers were reviewed and the same two reviewers (AR and TB) applied the inclusion criteria to the full text. Of these, 16 studies met the inclusion criteria and were included in this review. Two of these 16 were added after the hand search of reference lists of included papers (Figure 3.1). There was full consensus between the reviewers during the selection process of included papers.
3.3.2. Study results

3.3.2.1. Characteristics of participants and methods

There was no blinding of the examiners to the participant’s health status described. Most authors stated the baseline demographics in appropriate detail by including weight, height, age and gender (12/16, 75%), eight studies (50%) included a physical examination in order to validate their health status prior to study enrollment. Only one of the included studies reported calibration procedures of the force-plate [170], another one described procedures to ensure that the participants resumed an identical foot position throughout the trials [171].

Both subject demographics and health status for all studies are shown in Table 3.1. With regard to patient demographics, less than half of the included studies (41%) enrolled mixed gender groups of healthy and NSLBP participants. The studies employed rather broad age ranges of participants, with the most commonly enrolled age range being 21-40 years (76%).
### Table 3.1: Participant demographics and health status

<table>
<thead>
<tr>
<th>Study</th>
<th>Healthy status and number of participants</th>
<th>Gender</th>
<th>Age in years (SD)</th>
<th>Weight in kg (SD)</th>
<th>Height in cm (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luoto et al. [172]</td>
<td>moderate LBP: 68</td>
<td>Female</td>
<td>35</td>
<td>20-60</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>severe LBP: 51</td>
<td>Male</td>
<td>33</td>
<td>20-60</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy: 61</td>
<td></td>
<td>29</td>
<td>20-60</td>
<td>-</td>
</tr>
<tr>
<td>Mientjes et al. [173]</td>
<td>LBP: 8</td>
<td>Female</td>
<td>3</td>
<td>38.4</td>
<td>179</td>
</tr>
<tr>
<td></td>
<td>healthy: 8</td>
<td>Male</td>
<td>5</td>
<td>37.1</td>
<td>171</td>
</tr>
<tr>
<td>Kuukkanen et al. [174]</td>
<td>LBP: 90</td>
<td></td>
<td></td>
<td>39.9 (7.9)</td>
<td>-</td>
</tr>
<tr>
<td>Hamaoui et al. [175]</td>
<td>LBP: 10</td>
<td>Female</td>
<td>0</td>
<td>33</td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>healthy: 10</td>
<td>Male</td>
<td>10</td>
<td>31</td>
<td>178</td>
</tr>
<tr>
<td>Grimstone et al. [176]</td>
<td>LBP: 10</td>
<td></td>
<td></td>
<td>32 (8.3)</td>
<td>173 (10)</td>
</tr>
<tr>
<td></td>
<td>healthy: 10</td>
<td></td>
<td></td>
<td>26 (5.4)</td>
<td>171 (10)</td>
</tr>
<tr>
<td>Brumagne et al. [76]</td>
<td>LBP: 10</td>
<td></td>
<td></td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy: 10</td>
<td></td>
<td></td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Hamaoui et al. [177]</td>
<td>LBP: 10</td>
<td>Female</td>
<td>0</td>
<td>33</td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>healthy: 10</td>
<td>Male</td>
<td>10</td>
<td>31</td>
<td>178</td>
</tr>
<tr>
<td>Mok et al. [178]</td>
<td>LBP: 24</td>
<td></td>
<td></td>
<td>36.6 (10.)</td>
<td>171 (0.09)</td>
</tr>
<tr>
<td></td>
<td>healthy: 24</td>
<td></td>
<td></td>
<td>36.9 (10.5)</td>
<td>169 (0.08)</td>
</tr>
<tr>
<td>Smith et al. [179]</td>
<td>healthy / Induced LBP: 12</td>
<td>Female</td>
<td>4</td>
<td>26 (4)</td>
<td>176 (12)</td>
</tr>
<tr>
<td>della Volpe et al. [180]</td>
<td>LBP: 12</td>
<td>Male</td>
<td>8</td>
<td>35.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy: 12</td>
<td></td>
<td></td>
<td>35.4</td>
<td>-</td>
</tr>
<tr>
<td>Popa et al. [181]</td>
<td>LBP: 13</td>
<td>Female</td>
<td>6</td>
<td>35.1 (11.9)</td>
<td>147.4 (9.1)</td>
</tr>
<tr>
<td></td>
<td>healthy: 13</td>
<td>Male</td>
<td>7</td>
<td>32.2 (7.2)</td>
<td>174.4 (7.5)</td>
</tr>
<tr>
<td>Brumagne et al. [182]</td>
<td>LBP: 21</td>
<td></td>
<td></td>
<td>23.5 (1.0)</td>
<td>171.2 (10.2)</td>
</tr>
<tr>
<td></td>
<td>healthy: 24</td>
<td></td>
<td></td>
<td>23.0 (1.6)</td>
<td>172.9 (9.5)</td>
</tr>
<tr>
<td>Lafond et al. [183]</td>
<td>LBP: 12</td>
<td></td>
<td></td>
<td>41.5</td>
<td>172.0</td>
</tr>
<tr>
<td></td>
<td>healthy: 12</td>
<td></td>
<td></td>
<td>40.0</td>
<td>167.3</td>
</tr>
<tr>
<td>Harringe et al. [184]</td>
<td>LBP: 11</td>
<td></td>
<td></td>
<td>15.0</td>
<td>161</td>
</tr>
<tr>
<td></td>
<td>healthy: 18</td>
<td></td>
<td></td>
<td>13.8</td>
<td>160</td>
</tr>
<tr>
<td>Mann et al. [171]</td>
<td>LBP: 10</td>
<td>Female</td>
<td>10</td>
<td>57.6 (0.6)</td>
<td>165 (0.04)</td>
</tr>
<tr>
<td></td>
<td>healthy: 10</td>
<td>Male</td>
<td>0</td>
<td>57.6 (0.6)</td>
<td>-</td>
</tr>
<tr>
<td>Salavati et al. [185]</td>
<td>LBP: 22</td>
<td>Female</td>
<td>9</td>
<td>26.1 (6.2)</td>
<td>172 (0.1)</td>
</tr>
<tr>
<td></td>
<td>healthy: 22</td>
<td>Male</td>
<td>13</td>
<td>25.0 (5.5)</td>
<td>173 (0.1)</td>
</tr>
</tbody>
</table>

LBP: low back pain  
- : not described

While the majority of studies defined neurological pathologies such as nerve root irritations in their exclusion criteria, few studies specifically addressed excluding vestibular conditions [173, 174, 177]. Other neurological conditions affecting balance were not addressed. Only one study investigated whether NSLBP sufferers were under the influence of pain medication [14] and consequently excluded those patients.
Table 3.2 shows the study characteristics and the results of the most commonly used COP parameters. There is a marked heterogeneity present in the included studies in terms of sample duration, number of trials or choice of COP parameters used.

About 53% of the trials were performed under both eyes closed (EC) and eyes open (EO) conditions. Most of the authors conducted less than three repetitions of postural sway recordings (9/16, 56%). Mean velocity (mVel), mean distance/displacement, root mean square (RMS) as well as sway area accounted for most of the COP parameters selected (Table 3.2).

### Table 3.2: Study characteristics and selected COP parameters measured on a firm surface

<table>
<thead>
<tr>
<th>Study</th>
<th>Condition</th>
<th>Duration (sec)</th>
<th>Number of trials</th>
<th>Parameter</th>
<th>Low back pain Result (SD)</th>
<th>Healthy controls Result (SD)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luoto et al. [172]</td>
<td>normal stance, EO/F</td>
<td>25</td>
<td>1</td>
<td>mVel</td>
<td>female: A: 14mm/s B: 13mm/s</td>
<td>male: C: 12mm/s</td>
<td>p&gt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>female: A: 10mm/s B: 20mm/s</td>
<td>female: C: 11mm/s</td>
<td></td>
</tr>
<tr>
<td>Mientjes et al. [173]</td>
<td>normal stance, EO/EC, F/C</td>
<td>unclear</td>
<td>3</td>
<td>mPos RMS</td>
<td>-</td>
<td>-</td>
<td>p=0.099</td>
</tr>
<tr>
<td>Kuukkanen et al. [174]</td>
<td>unclear stance, EC/F</td>
<td>20 (40)</td>
<td>1</td>
<td>mVel (AP) RMS (ML) RMS (AP)</td>
<td>17.1mm/s (3.7)</td>
<td>-</td>
<td>p=0.016</td>
</tr>
<tr>
<td>Hamaoui et al. [175]</td>
<td>normal stance, EO/F</td>
<td>20</td>
<td>5</td>
<td>mPos (AP) mPos (ML)</td>
<td>2.9 mm (0.5) 1.6 mm (0.7)</td>
<td>1.9 mm (0.8) 1.1 mm (0.6)</td>
<td>p=0.002</td>
</tr>
<tr>
<td>Grimstone et al. [176]</td>
<td>normal stance, EO/F</td>
<td>120</td>
<td>1</td>
<td>mean displacement</td>
<td>3.2mm</td>
<td>2.4mm</td>
<td>-</td>
</tr>
<tr>
<td>Brumagne et al. [76]</td>
<td>normal stance, unclear visual condition/F</td>
<td>60</td>
<td>1</td>
<td>RMS (AP)</td>
<td>young: ~ 8mm elderly: ~7.5mm</td>
<td>young: ~5mm elderly: ~5mm</td>
<td>p&gt;0.05</td>
</tr>
<tr>
<td>Hamaoui et al. [177]</td>
<td>normal stance, EO/F</td>
<td>20</td>
<td>5</td>
<td>mean displacement</td>
<td>AP 4.3 mm (1.6) ML 2.0 mm (1.2)</td>
<td>AP 2.7 mm (0.9) ML 1.3 mm (0.6)</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td>Smith et al. [179]</td>
<td>normal stance, EC/EO/F</td>
<td>70</td>
<td>1</td>
<td>mVel</td>
<td>4.3mm/s (2.17)</td>
<td>5.03 mm/s (2.8)</td>
<td>p&gt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mean displacement</td>
<td>EC: ~2.9 mm</td>
<td>EC: ~2.75 mm</td>
<td>-</td>
</tr>
<tr>
<td>Mok et al. [178]</td>
<td>normal stance, narrow stance, EC/F</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>Task Details</td>
<td>mVel (AP)</td>
<td>RMS length</td>
<td>Area</td>
<td>p-value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>--------------</td>
<td>-------------------</td>
<td>------------</td>
<td>--------</td>
<td>---------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>della Volpe et al. [180]</td>
<td>normal stance, EO/F</td>
<td>12.18 mm/s (1.2)</td>
<td>0.19 mm (0.01)</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Popa et al. [181]</td>
<td>normal stance, EC/F</td>
<td>2.85 mm (0.02)</td>
<td>2.09 mm (0.01)</td>
<td>p&lt;0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brumagne et al. [182]</td>
<td>normal stance, EO/EC, F/C</td>
<td>RMS (AP)</td>
<td>EC/F: 8.8 mm</td>
<td>EC/F: 5.4 mm</td>
<td>p&gt;0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lafond et al. [183]</td>
<td>normal stance, EC/F</td>
<td>-5 mm/s</td>
<td>-3 mm/s</td>
<td>p&gt;0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harringe et al. [184]</td>
<td>normal stance, EC/F</td>
<td>2.2 mm/s (0.59)</td>
<td>2.06 mm/s (0.6)</td>
<td>p&gt;0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mann et al. [171]</td>
<td>normal stance, EC/F</td>
<td>-6.7 mm/s</td>
<td>-5 mm/s</td>
<td>p&gt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salavati et al. [185]</td>
<td>normal stance, EC/F</td>
<td>SD vel</td>
<td>AP: 13.0 mm/s</td>
<td>AP: 14.8 mm/s</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The results presented have been extracted from bar-charts.
† The results from uni- and bilateral static task conditions were not differentiated.


Although both height and weight have been shown to affect the reliability of COP measures [147, 186] none of the presented results was subject to a normalizing process for these factors. Normalizing refers to statistically removing the dependence of stabilometric parameters on biomechanical factors as originally proposed by O’Malley [27].

### 3.3.2.2. Reliability of COP data

Table 3.3 gives an overview of how the studies included meet the ideal experimental setup for reliable data as defined in Chapter 2. As this only provides a broad idea of how reliable the
results are, a closer look is at times necessary when interpreting the score. For example, the study by Lafond et al. [183] did not sample many recordings, but the extensive sampling duration of up to 30min can be expected to outweigh this shortcoming. The study by Luoto et al. [172] on the other hand clearly falls short of the ideal setup by recording sway only once for a total of 15sec.

As a general rule, the most important factors for reliable data appear to be sampling duration, number of trials and visual condition [92]. Irrespective of sampling frequency and cut-off frequency, a sufficient sampling duration (<90sec) in combination with the appropriate number of recordings (3-5) showed to yield reliable data for most COP parameters such as mean velocity (mVel) or area [136, 184, 187].

With few exceptions [172, 175, 176, 180, 183], most of the studies conducted the trials under visual deprivation while only four [176, 179, 183, 184] applied a sampling duration that has shown sufficient reliability [92]. A minority used three or more trial repetitions [171, 173, 177, 180, 181, 185].

Table 3.3: Reliability criteria

<table>
<thead>
<tr>
<th>Study</th>
<th>Recommended</th>
<th>Sampling frequency</th>
<th>Cut-off frequency</th>
<th>Duration</th>
<th>Number of repetitions</th>
<th>Visual condition</th>
<th>Surface</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luoto et al. [172]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Mentjes et al. [173]</td>
<td>0</td>
<td>0</td>
<td>unclear</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Kuukkanen et al. [174]</td>
<td>unclear</td>
<td>unclear</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Hamaoui et al. [175]</td>
<td>0</td>
<td>unclear</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Grimson et al. [176]</td>
<td>0</td>
<td>unclear</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>++</td>
</tr>
<tr>
<td>Brumagne et al. [76]</td>
<td>0</td>
<td>0</td>
<td>unclear</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Hamaoui et al. [177]</td>
<td>unclear</td>
<td>unclear</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Mok et al. [178]</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Smith et al. [179]</td>
<td>+</td>
<td>unclear</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>della Volpe et al. [180]</td>
<td>unclear</td>
<td>unclear</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>++</td>
</tr>
<tr>
<td>Popa et al. [181]</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Brumagne et al. [182]</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Lafond et al. [183]</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Harringe et al. [184]</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Mann et al. [171]</td>
<td>+</td>
<td>unclear</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Salavati et al. [185]</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
</tbody>
</table>

0= not fulfilled, + = fulfilled
3.3.2.3. Pain characteristics

Only half the studies (8/16, 50%) stated the total low back pain duration prior to the test (ranging from 1 to 10.5 years); the long-term implications of this factor on COP excursions cannot be assessed. Of all the studies only, a minority (6/16, 38%) correlated this duration to pain intensity (Table 3.4).

**Table 3.4:** Pain definition, intensity and characteristics of included studies

<table>
<thead>
<tr>
<th>Study</th>
<th>Physical examination</th>
<th>Low back pain *</th>
<th>Pain presence in years (SD)</th>
<th>Pain present at time of trial (n)</th>
<th>Pain intensity evaluation (pre-trial)</th>
<th>Score (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luoto et al. [172]</td>
<td>yes</td>
<td>chronic</td>
<td>-</td>
<td>yes (99/99)</td>
<td>VAS</td>
<td>unclear</td>
</tr>
<tr>
<td>Mientjes et al. [173]</td>
<td>-</td>
<td>chronic</td>
<td>10.9</td>
<td>yes (8/8)</td>
<td>VAS</td>
<td>2.6</td>
</tr>
<tr>
<td>Kuukkanen et al. [174]</td>
<td>yes</td>
<td>subacute</td>
<td>10 (8.4)</td>
<td>yes (58/58)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hamaoui et al. [175]</td>
<td>-</td>
<td>chronic</td>
<td>-</td>
<td>yes (10/10)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Grinstone et al. [176]</td>
<td>-</td>
<td>chronic</td>
<td>3.54</td>
<td>yes (10/10)</td>
<td>VAS</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Brumagne et al. [76]</td>
<td>-</td>
<td>chronic</td>
<td>-</td>
<td>unclear</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hamaoui et al. [177]</td>
<td>yes</td>
<td>chronic</td>
<td>-</td>
<td>yes (10/10)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mok et al. [178]</td>
<td>-</td>
<td>chronic</td>
<td>10.5 (8)</td>
<td>yes (24/24)</td>
<td>VAS</td>
<td>2.0 (1.6)</td>
</tr>
<tr>
<td>Smith et al. [179]</td>
<td>-</td>
<td>acute</td>
<td>-</td>
<td>yes (12/12)</td>
<td>VAS</td>
<td>4.4 (1.9)</td>
</tr>
<tr>
<td>della Volpe et al. [180]</td>
<td>yes</td>
<td>chronic</td>
<td>5.2</td>
<td>yes (12/12)</td>
<td>NRS-11</td>
<td>2.5-10</td>
</tr>
<tr>
<td>Popa et al. [181]</td>
<td>yes</td>
<td>chronic</td>
<td>5.2 (3.3)</td>
<td>yes (13/13)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Brumagne et al. [182]</td>
<td>-</td>
<td>chronic</td>
<td>3.4 (2.5)</td>
<td>yes (21/21)</td>
<td>VAS</td>
<td>2.2 (1.5)</td>
</tr>
<tr>
<td>Lafond et al. [183]</td>
<td>yes</td>
<td>chronic</td>
<td>-</td>
<td>yes (10/10)</td>
<td>VAS</td>
<td>2.5</td>
</tr>
<tr>
<td>Harringe et al. [184]</td>
<td>-</td>
<td>-</td>
<td>mostly (7/11)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mann et al. [171]</td>
<td>yes</td>
<td>chronic</td>
<td>-</td>
<td>yes (10/10)</td>
<td>VAS</td>
<td>6 (2)</td>
</tr>
<tr>
<td>Salavati et al. [185]</td>
<td>-</td>
<td>episodic</td>
<td>1.0</td>
<td>no (22/22)</td>
<td>VAS</td>
<td>&lt;2.0</td>
</tr>
</tbody>
</table>

* Chronic pain is defined as pain presence for at least 3 months.

Visual analogue scale (VAS) ranging from 0-10: 0-2: light pain, 3-5: light to moderate pain, 6-7: moderate to intense pain, 8-10: unbearable pain [188].

3.3.2.4. Pain assessment

Due to the described heterogeneity in the experimental setups, a direct comparison of data sets is problematic. Only about half of the studies described some form of physical examination prior to the recordings (9/16, 57%). While all investigated the effect of NSLBP on COP measures, not all studies (9/16, 57%) assessed the pain level in some form e.g. by
means of a visual analogue scale (VAS). Luoto et al. [172] mentioned collecting VAS data of their participants but this data is missing in the published paper.

The participants in two of the studies did not experience any pain at the time of recording [137, 176, 185], neither were four individuals of another [184]. While Brumagne et al. [182] stated that their participants were not in an acute recurrence of NSLBP; they nevertheless reported VAS scores of 2.2±1.5 and were consequently counted as in pain. The perceived pain levels were similar throughout the studies at around 2.5 (VAS), indicating mild to moderate pain (Table 3.4).

3.3.2.5. Low back pain and postural sway

Generally there is a great variability in the reported COP measures. The results of the included studies indicate that patients suffering from NSLBP exhibited a greater postural instability than healthy controls. This difference was statistically significant in the majority of studies (14/16, 88%). Only two studies found significantly lesser COP excursions in patients suffering from low back pain.

The variation in results can be observed irrespective of the particular COP parameter chosen. Compared to healthy controls, participants with NSLBP exhibited a greater sway area [183, 184], although only the readings of one study reached statistical significance [183]. Accounting for the different sampling durations, the reported results for greater COP area in NSLBP cases varied greatly between 7.11 cm² [184] and 18.5 cm² [183].
The NSLBP patients also showed an increased COP mean displacement [175-177, 179, 181]. This difference was significant in the AP direction [175, 177, 181]. The general trend towards an increased AP sway in pain sufferers was also present when considering the root mean square (RMS) for antero-posterior sway [182, 189], an effect that was found to increase with longer sampling durations [183]. Only two studies identified a decreased AP sway compared to healthy controls [178, 185].

Additionally, a higher COP sway velocity was found in non-specific LBP cases [171, 172, 180, 183, 184]. The mean velocities ranged from about 2.23 mm/s [184] to 17.1 mm/s [174] throughout the studies. For comparison, Table 3.5 shows the results for the parameter mean velocity.

### Table 3.5: The effect of NSLBP on postural sway for the COP parameter mean velocity

<table>
<thead>
<tr>
<th>Study</th>
<th>Duration (sec)</th>
<th>Number of trials</th>
<th>Healthy controls</th>
<th>LBP patients (SD)</th>
<th>Pain severity (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luoto et al. [172]</td>
<td>15</td>
<td>1</td>
<td>male: 12mm/s</td>
<td>male: 14mm/s</td>
<td>moderate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>female: 11mm/s</td>
<td>female: 10mm/s</td>
<td>severe</td>
</tr>
<tr>
<td>della Volpe et al. [180]</td>
<td>20</td>
<td>3</td>
<td>AP: 12.2 mm/s (1.2)</td>
<td>AP: 10.3 mm/s (0.6)</td>
<td>2-5 NRS-11</td>
</tr>
<tr>
<td>Lafond et al. [183] =</td>
<td>60</td>
<td>1</td>
<td>~3 mm/s</td>
<td>~5 mm/s</td>
<td>2.5 VAS</td>
</tr>
<tr>
<td>Mann et al. [171] =</td>
<td>30</td>
<td>1-3</td>
<td>~5 mm/s</td>
<td>~6.7 mm/s</td>
<td>6 (2) VAS</td>
</tr>
<tr>
<td>Salavati et al. [185]</td>
<td>30</td>
<td>3</td>
<td>15.9 mm/s (0.33)</td>
<td>13.7 mm/s (0.35)</td>
<td>&lt; 2.0 VAS</td>
</tr>
</tbody>
</table>

Visual analogue scale (VAS) ranging from 0-10. 0-2: light pain, 3-5: light to moderate pain, 6-7: moderate to intense pain, 8-10: unbearable pain [188].

NRS-11 ranging from 0 "no pain" to 10 "worst possible pain".

* The results presented have been extracted from bar-charts.

#### 3.3.2.6. The contribution of visual information

The results show that the differences in COP pattern between LBP sufferers and healthy controls gain significance under visual deprivation. An increase in postural sway in the
absence of visual input has been observed by numerous studies of healthy participants [171, 174, 181, 190]. In a study enrolling patients suffering from lumbar disc pathologies, the level of significance between those and healthy controls increased from \( p<0.05 \) (~12 mm/s compared to ~8 mm/s) under eyes open to \( p<0.01 \) (~23 mm/s and ~13 mm/s respectively) under eyes closed condition for COP mean velocity [190]. Mann et al. reported that the presence of visual input did not influence COP mean velocity in healthy subjects and no difference between healthy controls and LBP patients was observed under eyes open condition. With closed eyes, however, a significant difference became apparent (5mm/s compared to 6.7 mm/s, \( p=0.015 \)) [171].

3.3.2.7. Sampling duration

Most studies focused on investigating COP excursions of NSLBP sufferers during relatively short sampling durations of up to 120 seconds, observing the described increased postural instability. Only one study assessed body sway during prolonged standing of 30 minutes [183]. Initially, a decrease in COP mean sway velocity (mVel) in medio-lateral direction was observed during the first 15 minutes, followed by a significantly increased mVel compared to healthy controls in both antero-posterior and medio-lateral direction during the second 15 minutes of the sampling period.

3.3.2.8. Disability assessment

The study designs and variable participant’s health characteristics render any direct comparison of results problematic (Table 3.6). The majority of the included studies (12/16, 75%) investigated the perceived level of disability of the participants. Two of the papers [172,
174] failed to document the results, another one only assessed post-trial disability levels [173]. In addition to the Roland Morris [191] questionnaire, the Oswestry [192] questionnaire was the most commonly used (8/12, 67%). The scores generally show great variability ranging from 1-32/50 (Oswestry) and 3.2-17/24 (Roland Morris).

Table 3.6: Disability definition and characteristics of included studies

<table>
<thead>
<tr>
<th>Study</th>
<th>Disability assessed</th>
<th>Questionnaire</th>
<th>Score (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luoto et al. [172]</td>
<td>yes</td>
<td>Oswestry</td>
<td>unclear</td>
</tr>
<tr>
<td>Mientjes et al. [173]</td>
<td>yes</td>
<td>Oswestry (post-trial)</td>
<td>9-32 / 50 (mean 15.6)</td>
</tr>
<tr>
<td>Kuukkanen et al. [174]</td>
<td>no</td>
<td>Oswestry</td>
<td>unclear</td>
</tr>
<tr>
<td>Hamaoui et al. [175]</td>
<td>no</td>
<td>Oswestry (post-trial)</td>
<td>3-17 / 24 (mean 7.5)</td>
</tr>
<tr>
<td>Grimstone et al. [176]</td>
<td>no</td>
<td>Roland Morris (post-trial)</td>
<td></td>
</tr>
<tr>
<td>Brumagne et al. [176]</td>
<td>yes</td>
<td>Roland Morris</td>
<td>9-32 / 50 (mean 15.6)</td>
</tr>
<tr>
<td>Kuukkanen et al. [174]</td>
<td>no</td>
<td>Oswestry</td>
<td>unclear</td>
</tr>
<tr>
<td>Hamaoui et al. [177]</td>
<td>no</td>
<td>Oswestry</td>
<td>20/50</td>
</tr>
<tr>
<td>Mok et al.[178]</td>
<td>yes</td>
<td>Roland-Morris</td>
<td>3.2 (3.5) / 24</td>
</tr>
<tr>
<td>Smith et al. [179]</td>
<td>no</td>
<td>Oswestry</td>
<td>1-24 / 50 (mean 7.8)</td>
</tr>
<tr>
<td>della Volpe et al. [180]</td>
<td>yes</td>
<td>Oswestry</td>
<td>0-24 / 50 (mean 7.08)</td>
</tr>
<tr>
<td>Popa et al. [181]</td>
<td>yes</td>
<td>Oswestry</td>
<td>7.3 (7.6) / 100</td>
</tr>
<tr>
<td>Brumagne et al. [182]</td>
<td>yes</td>
<td>FABQ</td>
<td>12.6 / 50 (7.3)</td>
</tr>
<tr>
<td>Lafond et al. [183]</td>
<td>yes</td>
<td>FABQ</td>
<td>20.4 (16.2)</td>
</tr>
<tr>
<td>Harringe et al. [184]</td>
<td>no</td>
<td>Oswestry</td>
<td></td>
</tr>
<tr>
<td>Mann et al. [171]</td>
<td>no</td>
<td>Oswestry</td>
<td></td>
</tr>
<tr>
<td>Salavati et al. [185]</td>
<td>yes</td>
<td>Roland-Morris</td>
<td>3.4 (3.2) / 24</td>
</tr>
</tbody>
</table>

Roland Morris Disability Questionnaire [191]: 24 items, 0 (no disability) – 24 (severe disability).


FABQ: Fear Avoidance Belief Questionnaire [193]. 0-96, the higher the scale scores the greater the degree of fear and avoidance beliefs shown by the patient.

3.4. Discussion

Due to the heterogeneous study designs and experimental setups pooling of data was not possible. However, despite the great variability across the included studies our systematic review showed that patients suffering from NSLBP exhibit a significantly increased COP sway. Unfortunately, the magnitude of these differences in postural sway cannot be summarily
expressed in terms of specific percentages or values. As a result, only a general trend is noted.

As outlined in the previous chapter, the reliability of COP measurements is determined by factors such as sampling duration, sampling frequency and number of trials [187]. In our critical review only about half the included studies fulfilled three or more of these recommended reliability criteria. However, there was a trend towards better methodological reporting in the more recent studies. Despite this it is worth bearing in mind that studies with less than all six criteria may still present fairly reliable results.

The main reason for the heterogeneity of the studies is their use of different methods such as sampling duration, which varied considerably across the studies. Comparing mean sway velocities is more appropriate as this parameter is only indirectly time-dependent although it is still affected by too short sampling durations. With longer recording times the sway areas tend to increase and the further away the COP paths deviates from the center point, postural adaptations will require higher sway velocities to maintain balance. As with the sway area, significantly higher mean sway velocities have been reported in NSLBP patients.

Two studies, however, described decreased COP mean velocities of NSLBP sufferers compared to healthy controls [178, 185], which cannot be readily explained. The results presented by Mok et al. [178] did not allow differentiation between bilateral and unilateral stance conditions. This, however, does not account for a decrease in COP sway as one leg standing has shown an equal tendency for an increased postural instability in NSLBP sufferers [34]. As for the second study, Salavati et al. [185], did not state how many participants actually suffered from NSLBP at the time of recording. Although the absence of pain in a substantial number of participants may explain similar COP velocities to those of healthy individuals (as
will be discussed in Chapter 9), it does not explain lower values. However, inter-subject variability due to the fairly small sample size (n=22) may account for the observed results.

While there is broad consensus on increased COP excursions for sampling durations of up to 120sec, Lafond et al. [183] observed decreased postural sway in NSLBP patients during the first half of prolonged standing (total 30min). One possible explanation is that the participants were distracted by the film shown to them during the measurement and ignored the perceived discomfort, at least during the first 15min interval. This may result in the observed limited postural sway until the effect of pain became harder to compensate for, signified by the higher COP mean velocity observed during the second half.

With regards to vision, an increase in COP excursions has been observed under visual deprivation compared to eyes open condition in patients suffering from NSLBP. This supports the previously mentioned proprioceptive deficits in NSLBP patients. An existing impaired sensory input from muscles and joints is more severely challenged with closed eyes. Vision is primarily used in controlling low frequency disturbances [194], as occurring during quiet stance. In conjunction with vestibular information, it is essential for stabilizing upright posture. In patients with a reduction in proprioceptive input, as seen in chronic NSLBP, it is therefore common to find a greater reliance on visual and vestibular cues to maintain postural stability. Visual obstruction will therefore exhibit a profound effect on balance as the system is deprived of two major contributors for postural control.

The observed increased antero-posterior sway exhibited by NSLBP patients may also be related to the described deficits in proprioception in the hip region. This is believed to inhibit hip strategy and evoke the ankle strategy to maintain standing posture [189] with resulting larger sway in the antero-posterior direction. While ankle strategy is characterized by body sway resembling a single-segment inverted pendulum, hip strategy refers to a double-segment
version divided at the hip with the head and trunk moving in opposite directions to keep the center of pressure within the base of support [8, 29, 180]. The pronounced antero-posterior sway with the resulting raised ankle stiffness [61] observed in NSLBP sufferers may also be seen as an compensatory mechanism to enhance sensory discrimination and thereby compensate for the deterioration of the feedback loop [181].

Interestingly, the magnitude of COP excursions varies depending on the location of the pain. Experimentally induced pain into the biceps muscle, for example, did not exhibit any significant effect on postural sway [180], while a similar injection of levo-ascorbic acid (L-AS) into the feet elicited the same basic COP pattern found in chronic LBP sufferers. As the pain level was increased, so did the COP mean velocity and range in anterior-posterior direction [195].

3.4.1. Clinical application of COP measures

While this literature review shows that statistically significant differences in postural sway are present, the clinical application of COP measurements still remains limited for five major reasons described below.

Firstly, the causative factor for the altered postural sway is still unknown. The question remains whether the increased COP excursions are related to the previously described physiological changes due to chronic pain perception or rather acute “pain inhibition” [196]. If the latter mechanism is mainly responsible, monitoring NSLBP sufferers during their treatment and rehabilitation process may aid as an objective tool in assessing the patient’s progress. If long-term neuro-physiological changes are primarily involved, individually varying recovery time frames may render such measurements less useful.
To address this question, future research is recommended to compare groups of participants suffering from a) acute LBP without previous pain history to b) those asymptomatic but with a long pain history to c) healthy controls. This way, the direct effect of acute pain on postural stability can be assessed in the absence of physiological and neurological changes postulated with chronicity.

Secondly, the data available is insufficient to determine whether some form of linear or non-linear correlation between the perceived pain intensity and the magnitude of postural sway exists. At similar VAS scores, the reported results for COP mean velocity vary considerably. While one study reported a 100% increase in sway velocity with increasing pain perception [172], other studies showed no significant difference [171, 183].

Thirdly, the effect of pain duration, episodes of LBP and disability on COP excursions remain unclear. Due to the heterogeneous patient groups with a wide variety of pain durations and no information on the number of previous painful episodes being available, no conclusions can be drawn. Another contributing factor may be that self-reporting of LBP is prone to recall bias [197] and the definitions of NSLBP contained some variation throughout the studies. Both Oswestry and Roland-Morris results showed equally great variability which, in addition to the heterogeneous experimental setups, prevents interpretation. Further research is necessary to answer this question.

Fourthly, it has been shown that there is a steady natural increase in COP excursions with ageing [97]. The rather broad age-range of participants throughout the studies prevents an analysis of whether this also applies to pain-induced postural instability and how this magnitude correlates to specific age groups.
Finally, “normal” values are largely unknown and only one large-scale study offers reference values of healthy individuals for various COP parameters [97]. Similarly, reference data needs to be established for different LBP subgroups as a foundation for any intervention study. Until then, the identification of different COP patterns may be considered of academic rather than of clinical value at this time.

3.5. Conclusion

Patients with non-specific LBP exhibit greater postural instability than healthy controls. This difference is more pronounced under visual obstruction and can be attributed to either acute pain inhibition or diminished proprioceptive input from the lumbar spine and trunk muscles due to long-term neurological adaptations.

The increased postural sway in NSLBP sufferers further appears to be associated with the acute presence of pain. There is insufficient data to suggest a relationship between pain intensity, previous pain duration or the level of perceived disability and the magnitude of COP excursions.

The clinical application of COP measures is limited by the unknown origin of the altered sway pattern, as well as a lack of COP reference values for different gender and age groups under both healthy and NSLBP. Further research is necessary to address these issues.
3.6. Strengths and limitations

A potential limitation of this literature review is the search strategy and its limitation to seven databases which might not have identified all relevant papers. To overcome this, a dynamic search strategy was employed with selected hand searches of reference lists. Another limitation is the fact that only very few papers allowed for any direct inter-study comparison of results and many conclusions had to be drawn from those studies. However, the fact that two reviewers independently searched and appraised the literature constitutes a major strength of this study.
ALTERED POSTURAL SWAY IN PATIENTS SUFFERING FROM NON-SPECIFIC NECK PAIN AND WHIPLASH ASSOCIATED DISORDER- A SYSTEMATIC REVIEW

CHAPTER 4

Increased postural sway in patients suffering from non-specific neck pain and whiplash associated disorder - A systematic review of the literature

4.1. Background

Cervical pain is a common condition with a prevalence of around 40% [198] with 14% of the adult population progressing to a chronic state [199]. Irrespective of the type of neck pain, various theories exist about its general effect on kinaesthetic sense that are similar to pain originating from other areas. Ideally, the body should be able to generate quick center of pressure (COP) transitions that just exceed the current position of the center of mass (COM) [8] and accelerate it into the opposite direction in order to maintain balance. Any condition affecting the afferent sensory pathways may interfere with this process. The neck is particularly prone to this due to the abundant cervical sensory receptors in joints and muscles as well as their central and reflex connections to visual, vestibular and postural control systems.

As with NSLBP, the debate continues however, as to whether the cause of abnormal cervical afferent input is primarily proprioceptive or noxious in nature. Possible underlying mechanisms have been discussed in the previous chapter.

Despite clinical and biomechanical research efforts, the underlying mechanisms causing whiplash associated disorder (WAD) remain largely unknown [200]. In the absence of concurrent injury to head or vestibular apparatus, any impairments of postural stability may
reflect abnormal cervical afferent input to the postural control system. In WAD, facet joint components may be at risk for injury due to compression during rear-impact accelerations of 3.5g or more while capsular ligaments are at risk for injury at higher accelerations [200]. Depending on the magnitude of trauma, the resulting impairment of the sensory system is therefore likely to be more pronounced compared to cases of non-specific neck pain (NSNP).

This literature review will attempt to identify possible differences in COP pattern between subjects with WAD, NSNP sufferers and healthy controls that may relate to the mechanisms described above. To our knowledge no comprehensive systematic review has been conducted to investigate the possible impact of neck pain on COP pattern during bipedal static tasks and the possible association of this effect with pain intensity or disability.

Therefore, the aims of this systematic literature review are 1) to determine if there are significant differences in COP between non-specific neck pain and WAD patients and healthy controls, 2) to investigate whether the magnitude of these COP excursions are related to the level of pain perception or 3) to the perceived level of disability.

4.2. Methods

4.2.1. Search strategy

A comprehensive search strategy was developed by identifying all potentially relevant search terms, categorizing these terms into specific search phases and subsequently combining them by using Boolean terms. This search strategy was applied to seven different electronic databases: PubMed, MEDLINE, EMBASE, Web of Science, ScienceDirect, Digital Dissertations and the Cochrane library.
4.2.2. Electronic searches

All databases were searched using the search strategy described above. Appropriate minor modifications to the basic search template were made to optimize the strategy in each of the six databases. Papers were limited to human studies published between January 1980 and October 2010.

4.2.3. Searching other resources

The hand search included analyzing references cited in studies selected from the original online search. Citation searches of relevant studies were conducted using the PubMed, MEDLINE and ScienceDirect databases.

4.2.4. Selection Criteria

Papers were limited to peer-reviewed journals and dissertations without language restrictions. Wide inclusion and exclusion criteria for study designs were used to avoid limitation of potentially relevant papers.

The inclusion criteria were: Papers in any language that were fully or partially concerned with COP measures of subjects with non-specific neck pain or WAD derived from bipedal static task conditions on a forceplate, ideally compared to measures of healthy controls. For the purpose of this review, non-specific neck pain was broadly defined as pain in the neck of musculoskeletal origin in the absence of any neurological symptomatology or serious pathology such as cancer or infection. All COP measures, experimental setups and statistical
models fitting these criteria were considered and no limitations regarding patient demographics applied.

We excluded studies with insufficient documentation of patient demographics or experimental setup where this rendered data extraction impossible. In addition, papers that were anecdotal, speculative or editorial in nature or studies that employed dynamic task conditions such as one-leg hopping, walking or some form of translation of the force platform were excluded.

4.2.5. Data extraction and management

For the purpose of this review AR acted as the principal reviewer. A colleague (TB) was involved independently in the process of identifying relevant studies but did not participate in further analysis of the finally included papers. In case discrepancies between AR and TB were not reconciled by discussion, a third reviewer was used for a majority decision.

To standardize the procedure between the reviewers, the main author developed a detailed data extraction sheet to acquire general information on objectives, design, participant’s demographics and outcomes. This also facilitated critical appraisal where each study was individually analyzed. For procedure control a trial was conducted with two papers similar but unrelated to the review question and the results discussed. If any title and abstract did not provide enough information to decide whether or not the inclusion criteria were met, the article was included for the full text selection.

With regards to the research question, the data extraction consisted of three main areas regarding neck pain and disability: 1) self perceived pain intensity, 2) previous pain duration and 3) any reported disability level.
For the purpose of this review, induced neck pain (e.g. by injection or electric stimulation) in otherwise healthy participants is considered as non-specific neck pain.

4.2.6. Assessment of methodology

A recent study suggested that combined quality scores should not be incorporated into systematic reviews and instead the accuracy should be assessed by an investigation into individual quality scores [169]. Accordingly, the reviewers specifically assessed the application, documentation and association of six individual items with regards to differences in COP measures between neck pain patients and healthy controls.

The reviewed criteria regarding the experimental setups consisted of 1) subject demographics and morphology, 2) sampling duration, 3) number of COP recordings, 4) visual condition (eyes open or eyes closed), 5) stance (normal or narrow stance), and 6) platform surface (hard or foam). The studies were further assessed for the reliability of the experimental setup as outlined in our previous literature review [92].

4.3. Results

4.3.1. Literature search results

Initially, the database search strategy identified 203 studies of which abstracts were screened individually by the reviewers. The application of inclusion/exclusion criteria and consensus by the reviewers on the titles and abstracts eliminated a further 182 papers. From the titles and abstracts of papers selected (n=23), full papers were reviewed by the same two reviewers (AR and TB) who applied the inclusion criteria to the full text. Of these, 10 studies met the inclusion
criteria and were included in this review. One of these was added after the hand search of reference lists of included papers (Figure 4.1). There was full consensus between the reviewers during the selection process of included papers.

**Figure 4.1.** Flowchart of papers

4.3.2. Study results

4.3.2.1. Characteristics of participants and methods

General shortfalls in the documentation of technical aspects of COP acquisition were apparent, particularly with regard to sampling duration and cut-off frequency. In addition, surprisingly few authors described the baseline demographics of the participants in appropriate detail, leaving out weight, height, age and gender (3/10, 30%). There were no reports on calibration of the forceplate, no blinding of examiners and no described procedures to ensure that the participants resumed an identical foot position throughout the trials in studies using more than one recording.
Both subject demographics and health status for all studies are shown in Table 4.1. The number of symptomatic participants and the matching number of controls was generally small and ranged between seven [201] and fifty [202]. With regard to patient demographics, all but two of the included studies (8/10, 80%) enrolled mixed gender groups of healthy and symptomatic participants. The studies employed different age ranges of participants, with 20-40 years being most commonly enrolled (7/10, 70%).

Table 4.1: Participant demographics and health status

<table>
<thead>
<tr>
<th>Study</th>
<th>Participant status</th>
<th>Gender (n)</th>
<th>Age in years</th>
<th>Weight in kg</th>
<th>Height in cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>McPartland et al. [201]</td>
<td>NSNP * healthy *</td>
<td>6 Female   4 Male</td>
<td>39.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Michaelson et al. [203]</td>
<td>chronic NSNP healthy</td>
<td>9         0</td>
<td>40 (9)</td>
<td>73 (18)</td>
<td>165 (7)</td>
</tr>
<tr>
<td></td>
<td>chronic WAD healthy</td>
<td>6         3</td>
<td>44 (10)</td>
<td>79 (14)</td>
<td>171 (10)</td>
</tr>
<tr>
<td>Madeleine et al. [204]</td>
<td>chronic WAD * healthy/ induced NP</td>
<td>7         4</td>
<td>33.3 (6.7)</td>
<td>73.4 (11.4)</td>
<td>173.3 (7.2)</td>
</tr>
<tr>
<td>Treleaven et al. [202]</td>
<td>WAD (dizziness) healthy</td>
<td>38        12</td>
<td>35.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>WAD (no dizziness) healthy</td>
<td>38       12</td>
<td>35.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storaci et al. [205]</td>
<td>WAD healthy</td>
<td>24        16</td>
<td>28.4 (8.8)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>23        17</td>
<td>33.9 (12.7)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Endo et al. [206]</td>
<td>WAD healthy</td>
<td>19        13</td>
<td>39.0 (10.1)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>4         16</td>
<td>37.9 (9.3)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Treleaven et al. [207]</td>
<td>WAD healthy</td>
<td>15        5</td>
<td>46.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>14        6</td>
<td>49.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Field et al. [208]</td>
<td>WAD NSNP healthy</td>
<td>24        5</td>
<td>30.3 (1.3)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>23        7</td>
<td>27.9 (1.3)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Poole et al. [209]</td>
<td>NSNP healthy</td>
<td>20        0</td>
<td>65-82</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>20        0</td>
<td>65-82</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vuillerme et al. [210]</td>
<td>healthy/induced NP healthy</td>
<td>0        16</td>
<td>22.2 (1.8)</td>
<td>73.0 (11.8)</td>
<td>181.4 (6.4)</td>
</tr>
</tbody>
</table>

NP: neck pain, NSNP: non-specific neck pain, SD: standard deviation, WAD: whiplash-associated disorder
* one patient and one control participants did not participate in COP measurement
- : not described
All values are mean (SD).

Only one of the studies investigating postural sway in NSNP patients reported any associated neurological or vestibular symptomatology with two cases of vertigo and one of unsteadiness [208]. With regards to WAD patients, one study reported cases of vertigo and unsteadiness.
[203], another enrolled patients experiencing vertigo and dizziness [206]. The other studies either did not report on these symptoms [204] or stated their absence [208].

There was a marked variation present in the included studies in terms of sampling duration, number of trials or the selection of the COP parameters. The studies often employed a combination of different positional and visual setups in order to investigate postural sway in various challenging positions. The resulting variation in results can be observed irrespective of the COP parameter chosen.

Table 4.2 shows the study characteristics for sway assessment in NSNP sufferers. The majority of trials were performed under both eyes open (EO) and eyes closed (EC) condition (4/6, 67%) with only a single repetition (5/6, 83%). Sway area and root mean square (RMS) amplitude were the most commonly used COP parameters.

### Table 4.2: Study characteristics and selected COP parameters measured in NSNP sufferers

<table>
<thead>
<tr>
<th>Study</th>
<th>Condition</th>
<th>Duration (sec)</th>
<th>Number of trials</th>
<th>Parameter</th>
<th>Neck pain Result (SD)</th>
<th>Healthy controls Result (SD)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>McPartland et al. [201]</td>
<td>normal stance EO/EC/F</td>
<td>30</td>
<td>6</td>
<td>absolute sway Vel †</td>
<td>EO/F: 4.2 EC/F: 4.3</td>
<td>EO/F: 3.3 EC/F: 3.4</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td></td>
<td>narrow stance EO/EC/F</td>
<td>30</td>
<td>6</td>
<td>absolute sway Vel †</td>
<td>EO/F: 4.4 EC/F: 5.3</td>
<td>EO/F: 3.7 EC/F: 4.4</td>
<td>ns</td>
</tr>
<tr>
<td>Michaelson et al. [203]</td>
<td>narrow stance, EO/EC/F</td>
<td>20</td>
<td>1</td>
<td>sway area (mm²)</td>
<td>EO: 105 (73) EC: 166 (117)</td>
<td>EO: 66 (47) EC: 109 (65)</td>
<td>ns</td>
</tr>
<tr>
<td>Madeleine et al. [204]</td>
<td>narrow stance, EO/F</td>
<td>45</td>
<td>1</td>
<td>displacement ampl. AP (mm)</td>
<td>EO: ~2.7 *</td>
<td>EO: ~2.1</td>
<td>-</td>
</tr>
<tr>
<td>Field et al. [208]</td>
<td>normal stance EO/EC/F/C</td>
<td>30</td>
<td>1</td>
<td>AP RMS amplitude (mm)</td>
<td>EO/F: ~1.3 EC/F: ~1.4</td>
<td>EO/F: ~1.2 EC/F: ~1.1</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ML RMS amplitude (mm)</td>
<td>EO/C: ~2.2 EC/C: ~2.5</td>
<td>EO/C: ~2.3 EC/C: ~2.4</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/F: ~2.6 EC/F: ~3.4</td>
<td>EO/F: ~2.8 EC/F: ~4.1</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/C: ~4.1 EC/C: ~6.2</td>
<td>EO/C: ~5.6 EC/C: ~5.6</td>
<td>ns</td>
</tr>
<tr>
<td>Study</td>
<td>Surface Type</td>
<td>Condition</td>
<td>AP RMS Amplitude (mm)</td>
<td>ML RMS Amplitude (mm)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>-----------------------------------------</td>
<td>--------------</td>
<td>-----------</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poole et al. [209]</td>
<td>Narrow</td>
<td>EO/EC/F/C</td>
<td>EO/F: -3.3</td>
<td>EO/C: -3.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>EC/EO/F/C</td>
<td>EO/F: -4.5</td>
<td>EO/C: -4.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EC/O: -4.5</td>
<td>EO/C: -4.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EC/O: -7.6</td>
<td>EO/C: -6.9</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>EO/F: -5.2</td>
<td>EO/C: -5.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EO/C: -6.5</td>
<td>EO/F: -5.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vuillerme et al. [210]</td>
<td>Narrow</td>
<td>EC/EO/F/C</td>
<td>EO/F: -2.3</td>
<td>EO/C: -3.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>EC/EO/F/C</td>
<td>EO/F: -5.0</td>
<td>EO/C: -3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EO/O: -5.8</td>
<td>EO/C: -4.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EO/C: -7.5</td>
<td>EO/C: -6.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EO/F: -1.7</td>
<td>EO/C: -1.8</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EO/C: -1.9</td>
<td>EO/F: -1.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EO/O: -3.8</td>
<td>EO/C: -2.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EO/C: -3.8</td>
<td>EO/C: -3.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The results presented have been extracted from bar-charts.

* Induced neck pain cases and healthy participants are identical.

- : not described

†: unit not described

AP: antero-posterior, BP: bipedal, displ. ampl: displacement amplitude, C: compliant (foam) surface, EC: eyes closed, EO: eyes open, F: firm surface, ML: medial-lateral, mPos: mean position, mVel: mean velocity, ns: not significant (p>0.05), RMS: root mean square, vel: velocity

All values are mean (SD)

The study characteristics for trials enrolling WAD patients are presented in Table 4.3. Only a single recording was used in most cases (6/7, 86%), but in contrast to the NSNP studies, all study designs employed both visual conditions.
Table 4.3: Study characteristics and selected COP parameters measured in WAD sufferers

<table>
<thead>
<tr>
<th>Study</th>
<th>Condition</th>
<th>Duration (sec)</th>
<th>Number of trials</th>
<th>Parameter</th>
<th>WAD Result (SD)</th>
<th>Healthy controls Result (SD)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michaelson et al. [203]</td>
<td>narrow stance, EO/EC/F</td>
<td>20</td>
<td>1</td>
<td>sway area (mm²)</td>
<td>EO: 96 (57)</td>
<td>EO: 66 (47)</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: 269 (147)</td>
<td>EC: 109 (65)</td>
<td>p&lt;0.01</td>
</tr>
<tr>
<td>Madeleine et al. [204]</td>
<td>narrow stance, EO/EC/F</td>
<td>45</td>
<td>1</td>
<td>displacement ampl. AP (mm)</td>
<td>EO: ~4.6</td>
<td>EO: ~2.1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: ~6.0</td>
<td>EC: ~2.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>displacement ampl. ML (mm)</td>
<td>EO: ~2.2</td>
<td>EO: ~1.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: ~3.2</td>
<td>EC: ~1.2</td>
<td>-</td>
</tr>
<tr>
<td>Treleaven et al. [202]</td>
<td>normal stance, EO/EC/F/C</td>
<td>30</td>
<td>1</td>
<td>total energy</td>
<td>EO/F: ~0.80</td>
<td>EO/F: ~0.66</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/F: ~0.93</td>
<td>EC/F: ~0.70</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/C: ~1.30</td>
<td>EO/C: ~1.15</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~1.52</td>
<td>EC/C: ~1.38</td>
<td>ns</td>
</tr>
<tr>
<td>Storaci et al. [205]</td>
<td>unclear stance, EO/EC/F</td>
<td>-</td>
<td>2</td>
<td>sway area (mm²)</td>
<td>EO: 136.6 (76.3)</td>
<td>EO: 84.1 (44.8)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: 246.3 (127)</td>
<td>EC: 180.1 (102)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>path length (mm)</td>
<td>EO: 407.5 (103)</td>
<td>EC: 338.5 (85.6)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: 565.8 (151)</td>
<td>EC: 494.5 (145)</td>
<td>-</td>
</tr>
<tr>
<td>Endo et al. [206]</td>
<td>unclear stance, EO/EC/F</td>
<td>60</td>
<td>1</td>
<td>sway area (mm²)</td>
<td>EO: 102.8 (109)</td>
<td>EO: 35.0 (14.7)</td>
<td>p&lt;0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: 216.6 (207)</td>
<td>EC: 41.9 (25.2)</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mVel (mm/s)</td>
<td>EO: 18.6 (12.5)</td>
<td>EC: 13.8 (4.3)</td>
<td>p&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: 32.8 (22.2)</td>
<td>EC: 17.9 (6.0)</td>
<td>p&lt;0.001</td>
</tr>
<tr>
<td>Treleaven et al. [207]</td>
<td>normal stance, EO/EC/F/C</td>
<td>-</td>
<td>1</td>
<td>total energy</td>
<td>EO/F: ~1.2</td>
<td>EO/F: ~0.7</td>
<td>p&lt;0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/F: ~1.6</td>
<td>EO/C: ~1.2</td>
<td>p&lt;0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~1.4</td>
<td>EO/C: ~0.9</td>
<td>p&lt;0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/C: ~1.9</td>
<td>EO/C: ~1.6</td>
<td>p&lt;0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/F: ~0.6</td>
<td>EO/F: ~0.2</td>
<td>p&lt;0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/F: ~0.7</td>
<td>EO/C: ~0.7</td>
<td>p&lt;0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~1.3</td>
<td>EO/C: ~0.7</td>
<td>p&lt;0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~1.5</td>
<td>EO/C: ~0.9</td>
<td>p&lt;0.01</td>
</tr>
<tr>
<td>Field et al. [208]</td>
<td>normal stance, EO/EC/F/C</td>
<td>30</td>
<td>1</td>
<td>total energy</td>
<td>EO/F: ~1.4</td>
<td>EO/F: ~1.1</td>
<td>ns</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>EC/F: ~1.6</td>
<td>EO/C: ~1.3</td>
<td>p&lt;0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~1.6</td>
<td>EO/C: ~1.3</td>
<td>p&lt;0.02</td>
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<td></td>
<td></td>
<td></td>
<td>EO/C: ~1.9</td>
<td>EO/C: ~1.6</td>
<td>p&lt;0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/F: ~1.5</td>
<td>EO/F: ~1.3</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/C: ~1.7</td>
<td>EO/C: ~1.5</td>
<td>p&lt;0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~1.9</td>
<td>EO/C: ~1.9</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>narrow stance, EO/EC/F/C</td>
<td>-</td>
<td>1</td>
<td>total energy</td>
<td>EO/F: ~1.4</td>
<td>EO/F: ~1.2</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/F: ~1.5</td>
<td>EO/F: ~1.1</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/C: ~1.6</td>
<td>EO/C: ~1.3</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~3.9</td>
<td>EO/C: ~2.4</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ML RMS amplitude (mm)</td>
<td>EO: ~2.9</td>
<td>EO: ~2.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: ~3.5</td>
<td>EC: ~2.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/C: ~5.0</td>
<td>EO/C: ~4.1</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~7.0</td>
<td>EC/C: ~5.6</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td>narrow stance, EO/EC/F/C</td>
<td>30</td>
<td>1</td>
<td>AP RMS amplitude (mm)</td>
<td>EO/F: ~4.2</td>
<td>EO/F: ~3.1</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/F: ~4.8</td>
<td>EO/F: ~4.0</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/C: ~5.3</td>
<td>EO/C: ~4.4</td>
<td>p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~7.9</td>
<td>EO/C: ~6.9</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ML RMS amplitude (mm)</td>
<td>EO: ~5.5</td>
<td>EO: ~5.1</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: ~6.3</td>
<td>EC: ~5.6</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/C: ~6.3</td>
<td>EO/C: ~6.0</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~9.2</td>
<td>EC/C: ~8.2</td>
<td>ns</td>
</tr>
</tbody>
</table>

- : not described, = The results presented have been extracted from bar-charts.

All values are mean (SD).

Although both height and weight have been shown to affect the reliability of COP measures [147, 186], none of the presented studies implemented a normalizing process for these factors. Normalizing refers to statistically removing the dependence of stabilometric parameters on biomechanical factors as originally proposed by O’Malley [145].

### 4.3.2.2. Reliability of COP data

Table 4.4 gives an overview of how the studies included meet the ideal experimental setup for reliable data.

<table>
<thead>
<tr>
<th>Study</th>
<th>Sampling frequency</th>
<th>Cut-off frequency</th>
<th>Duration</th>
<th>Number of repetitions</th>
<th>Visual condition</th>
<th>Surface</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>McPartland et al. [201]</td>
<td>0</td>
<td>+</td>
<td>90sec</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++++</td>
</tr>
<tr>
<td>Michaelsen et al. [203]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Madeleine et al. [204]</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++++</td>
</tr>
<tr>
<td>Treleaven et al. [202]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Storaci et al. [205]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Endo et al. [206]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Treleaven et al. [207]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Field et al. [208]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Poole et al. [209]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Vuillerme et al. [210]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

With the exception of one paper that only measured postural sway under visual deprivation [210], all of the studies included assessed COP with both eyes open and eyes closed. No study applied the best practice experimental setup throughout.
4.3.2.3. Pain assessment and physical examination

All patients experienced pain at the time of recording. About 75% of studies described the total neck pain duration prior to the COP measurements whereby the pain history ranged from acute, induced pain to 97 (SD 68) months. Of these studies, half (5/8, 63%) assessed both the duration and the perceived pain intensity by using either the visual analogue scale (VAS) [202, 203, 208, 210] or the 11-box numeric rating scale (NRS-11) [204].

The perceived pain levels varied between the studies (Table 4.5). The pain intensity of WAD patients ranged between VAS 2.2 (SD 0.9) [208] and 4.9 (SD 2.3) [203], indicating mild to moderate pain. NSNP sufferers perceived pain within a similar range and rated their intensity from VAS 3.2 (SD 0.4) [208] to 5.2 (SD 1.6) [203].

Table 4.5: Pain definition, intensity and characteristics of included studies

<table>
<thead>
<tr>
<th>Study</th>
<th>WAD</th>
<th>NSNP</th>
<th>Pain presence in months (SD)</th>
<th>Pain present at time of trial</th>
<th>Pain intensity evaluation (pre-trial)</th>
<th>Score mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McPartland et al. [201]</td>
<td>X</td>
<td>-</td>
<td>yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Michaelson et al. [203]</td>
<td>X</td>
<td>87 (77)</td>
<td>yes</td>
<td>VAS</td>
<td>4.9 (2.3)</td>
<td></td>
</tr>
<tr>
<td>Madeleine et al. [204]</td>
<td>X</td>
<td>97 (68)</td>
<td>yes</td>
<td>VAS</td>
<td>5.2 (1.6)</td>
<td></td>
</tr>
<tr>
<td>Treleaven et al. [202]</td>
<td>X</td>
<td>induced</td>
<td>yes</td>
<td>NRS-11</td>
<td>6.0 (0.7)</td>
<td></td>
</tr>
<tr>
<td>Michaelson et al. [203]</td>
<td>X</td>
<td>87 (77)</td>
<td>yes</td>
<td>VAS</td>
<td>2.6-4.5 (0.5)</td>
<td></td>
</tr>
<tr>
<td>Madeleine et al. [204]</td>
<td>X</td>
<td>induced</td>
<td>yes</td>
<td>NRS-11</td>
<td>2.6-4.5 (0.5)</td>
<td></td>
</tr>
<tr>
<td>Treleaven et al. [202]</td>
<td>X</td>
<td>-</td>
<td>yes</td>
<td>VAS</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>Storaci et al. [205]</td>
<td>X</td>
<td>-</td>
<td>yes</td>
<td>VAS</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>Endo et al. [206]</td>
<td>X</td>
<td>6</td>
<td>yes</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Treleaven et al. [207]</td>
<td>X</td>
<td>17</td>
<td>yes</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Field et al. [208]</td>
<td>X</td>
<td>≥ 3</td>
<td>yes</td>
<td>VAS</td>
<td>2.2 (0.9)</td>
<td></td>
</tr>
<tr>
<td>Poole et al. [209]</td>
<td>X</td>
<td>≥ 3</td>
<td>yes</td>
<td>VAS</td>
<td>3.2 (0.4)</td>
<td></td>
</tr>
<tr>
<td>Vuillerme et al. [210]</td>
<td>X</td>
<td>&gt; 5</td>
<td>yes</td>
<td>VAS</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

- : not reported, NDI: Neck Disability Index, NSNP: non-specific neck pain, SD: standard deviation, WAD: whiplash associated disorder

Visual Analogue Scale (VAS) ranging from 0-10: 0-2: light pain, 3-5: light to moderate pain, 6-7: moderate to intense pain, 8-10: unbearable pain.
4.3.2.4. Neck pain and postural sway

Generally there was a great variability in the reported COP measures. The results of the included studies indicate that patients suffering from any form of neck pain exhibited a greater postural instability than healthy controls, a difference that was more pronounced in WAD patients.

In NSNP patients, a significant difference compared to healthy individuals was only observed in a minority of recordings (9/38, 24%) across all positional and visual conditions. Statistical significance was reached only in normal stance under visual deprivation of a firm surface [208-210] as well as with open eyes on both firm [201] and compliant surface [209]. In narrow stance the differences reached p≤0.05 with eyes open [209] and closed [208] on a firm surface as well as on a foam pad with eyes open [209]. One study failed to report levels of significance [203].

In cases of acutely induced neck pain by injection of hypertonic saline [204] or painful electrical stimulation to neck musculature [210], a marked increase in postural sway could be observed. While Vuillerme et al. [210] found a significantly increased mean sway velocity and area, no p-values were presented for the study by Madeleine et al. [204].

WAD sufferers also showed an increased postural sway, signified by a greater COP sway area [203, 205, 206], root mean square (RMS) amplitude and mean sway velocity [206]. In contrast to NSNP patients, the variance in COP excursion compared to healthy controls was significant in the majority of experimental setups, although two studies did not report levels of significance [204, 211].
With sampling durations ranging from 20 sec [203] to 60 sec [206], the reported results for COP area were fairly consistent between 218.6 mm² (SD 207) [206] and 269 mm² (SD 147) [203]. The WAD patients also showed an increased COP RMS amplitude [208] and displacement amplitude [204]. As with NSNP, the increase in postural sway in antero-posterior (AP) direction was more significant than in the medio-lateral (ML) plane [204, 208] (Table 4.4).

4.3.2.5. Disability assessment

Only three studies [202, 208, 209] assessed the level of disability in neck pain patients by means of the neck disability index (NDI) [212]. The NSNP patients scored NDI disability percentages between 21.5% (SD 1.4) [208] and 23.95% (SD 2.3) [209] while WAD sufferers had higher levels of impairment at 36.9% (SD 2.8) [208]. Scores from 21-40% indicate moderate disability.

4.4. Discussion

The heterogeneous study designs and experimental setups did not allow pooling of data or any direct comparison of results across the studies. In addition, the poor overall documentation of the experimental setups, particularly with regards to participant demographics and technical aspects such as sampling frequency and cut-off frequency, impaired full interpretation.

The included studies also often failed to offer a clear definition of the parameters chosen. This inhibits interpretation, particularly if the same units are used. Vuillerme et al. [210] for example
employed "variance" in mm², but it remains unclear how this relates to the rather often used parameter sway area (mm²).

However, despite the great variability the results allow us to conclude that patients suffering from neck pain or WAD exhibit an increased COP sway compared to healthy individuals, especially in AP direction.

The finding of decreased postural stability is consistent with studies investigating body sway in neck pain sufferers by other means [207, 213-215] as well as with COP measures in patients with non-specific low back pain [175, 177, 181]. Unfortunately, the magnitude of these differences in postural sway cannot be summarily expressed in terms of specific percentages or values. As a result, only a general trend is noted.

As outlined in Chapter 2, the reliability of COP measurements is primarily determined by the six main factors: sampling duration, sampling frequency, cut-off frequency, platform surface (firm/compliant), foot position and the number of recordings. Although only two of the included studies fulfilled more than half of the recommended reliability criteria [201, 204], it is worth bearing in mind that studies considering less than all six criteria may still present fairly reliable results.

While a general trend towards decreased postural stability can be observed irrespective of the origin of the pain, the altered sway pattern appears to correlate with the associated degree of proprioceptive impairment. This is signified by the generally greater COP excursions in WAD cases [203, 204, 208] where damage to proprioceptive structures and neck musculature due to the sustained trauma may be expected. In addition, the underlying neurological or vestibular impairments observed in several studies [203, 206] may be the determining factor in the reported highly significant differences in sway pattern compared to healthy controls.
We have decided to include studies using induced pain in our review. While this cannot be considered similar to (chronic) NSNP, it may nevertheless mimic many alterations in sensorimotor functions documented in acute clinical pain conditions, although it should be noted that it does not replicate potential long term neurological adaptation. It is difficult to draw conclusions regarding the effect of an acute pain stimulus in otherwise healthy individuals as the two studies employing it used heterogeneous methods and sites of stimulation [204, 210]. Both experiments resulted in significantly altered sway pattern which may underlie the role of acute "pain inhibition" [196] in the observed postural response. However, the COP sway area measured was nevertheless smaller than reported in WAD sufferers [204] which may underlie the likely role of proprioceptive impairment associated with the pain in the development of COP excursions of larger magnitude.

Visual deprivation caused an increase in postural sway in numerous studies of healthy participants [171, 174, 181, 190] and has shown to be a major challenge to the balance systems in studies investigating the effect of non-specific low back pain on postural sway [175, 177, 181]. It is therefore quite surprising that recordings under this condition failed to elicit statistically significant differences in a number of measures of NSNP cases, especially in unstable conditions such as narrow stance (Table 4.2). In addition to issues arising from the experimental setups and the generally very small sample sizes of seven [201] to thirty [208] symptomatic participants, the varying perceived pain intensities may offer an explanation.

If rather small differences in COP measures between the groups can be anticipated, the choice of appropriate sway parameters is important. However, only Vuillerme et al. [210] and Endo et al. [206] used mean velocity (mVel), a parameter that has shown both consistently high reliability [92] and discriminative value in pain conditions [216]. Despite a small sample size and low scores for the reliability of the experimental setup, they found highly significant differences with eyes open [206] and under both visual conditions [210].
The effect of ageing can be observed when comparing the studies by Field et al. [208] and Poole et al. [209]. Although the methodologies are very similar, varying results were reported. This may be explained by the fact that the latter enrolled elderly patients (65-82 years compared to 27-30 years). Older individuals exhibit increased COP excursions [97] and any pre-existing deficits in proprioception associated with ageing may add to the alterations caused by the neck pain. Although Poole et al. [209] enrolled only female participants, a contributing gender effect is unlikely as about 70% of the mixed-gender group used by Field et al. [208] were also female.

Overall, the lack of data available, no conclusions can be drawn regarding a possible relationship between postural stability and perceived pain or disability levels. For the same reason, no conclusion about the effect of impairments in cervical ROM is possible.

4.4.1. Clinical considerations

At this point, there are several important limitations to the application of COP measures in the assessment of postural sway in a clinical setting:

Although the results tempt us to hypothesize a correlation between the magnitude of COP excursions and the extent of damage to proprioceptive structures, the causative factor for the altered postural sway pattern remains largely unclear in WAD and NSNP sufferers. The question still remains whether the increased COP excursions are predominantly related to the previously described physiological changes due to chronic pain perception, acute or chronic damage to proprioceptive structures in the neck or acute “pain inhibition” [196]. If the latter mechanism is mainly responsible or if the proprioceptive impairment is of acute and reversible nature, monitoring neck pain sufferers during their treatment and rehabilitation process may
aid as an objective tool in assessing the patient’s progress. If long-term neuro-physiological changes are primarily involved, individually varying recovery time frames may render such measurements less useful.

Finally, the data available is insufficient to determine whether some form of correlation between the neck pain intensity, its duration or the perceived disability and the magnitude of postural sway exists. As a linear relationship between pain intensity and COP sway velocity has been demonstrated in patients with non-specific low back pain [217], further research is necessary to investigate whether this also applies to neck pain sufferers. If this can be established COP may have a clinical role as an instrument of measurement for neck pain sufferers.

4.4.2. Limitations

Although employing two reviewers to individually search the literature constitutes a major strength of this review, there are limitations. For example, the search strategy was limited to six key databases which might not have identified all relevant papers. To overcome this, a dynamic search strategy was employed with selected hand searches of reference lists. Due to the aim of this review, only COP measures derived from bipedal static tasks were included.

4.5. Conclusion

Patients with neck pain of both whiplash associated disorder and non specific neck pain exhibit greater postural instability than healthy controls. This difference is more pronounced under visual obstruction and may be attributed to either acute pain inhibition or diminished
proprioceptive input from the cervical spine and neck muscles. This may be due to long-term neurological adaptations although additional cognitive and behavioral factors cannot be ruled out. WAD sufferers show greater COP excursions than NSNP patients and this may be due to the potentially increased damage to cervical proprioceptive structures associated with the sustained neck trauma.

While the presence of pain itself appears associated with increased postural sway, there is insufficient data to suggest a relationship between pain intensity, previous pain duration or the level of perceived disability and the magnitude of COP excursions.
THE ASSOCIATION BETWEEN THERAPEUTIC INTERVENTIONS AND POSTURAL STABILITY - A LITERATURE REVIEW

CHAPTER 5

The association between therapeutic interventions and postural stability – a literature review

5.1. Background

It is not uncommon for the restoration of postural stability and balance to be a goal of therapeutic interventions [218]. Changes in COP excursions as a measure of balance performance are often used for this purpose, and commonly so in association with therapeutic exercise [174, 219, 220] or balance training [221-223]. The role of manual therapies, however, remains unclear. If alterations in postural sway following manual therapies are observed, an interesting question may be whether such a change in COP was associated with pain reduction.

In several studies of manipulation for spinal pain there have been some reports of improvement in side-to-side weight bearing [224] and balance performance when measured with a Berg balance scale (BBS) [225-228]. It appears likely that any change in COP excursions associated with this sort of manual therapy is due to a reduction in pain intensity [229, 230]. However, it may also be legitimate to hypothesize that a therapeutic intervention capable of increasing somatosensory function may be beneficial for postural stability. Cervical spinal manipulative therapy (SMT), for example, has been shown to improve proprioception [231, 232], although the underlying mechanism remains unclear.

With regards to alterations in post-intervention COP measures associated with manual therapies, however, there is a profound lack of evidence and only a few studies of quality have
been published. This literature review will present and critically comment on the current state of knowledge.

The objective of this literature review is to 1) determine if there are significant changes in postural stability associated with manual therapeutic interventions, 2) investigate whether these changes occur in pain sufferers, healthy individuals or both and 3) whether any observed postural sway alterations are related to factors such as the pain intensity associated with the underlying condition of the symptomatic individuals.

5.2. Methodology

Initially, a search of papers was limited to peer-reviewed journals. However, due to the limited yield the inclusion and exclusion criteria were extended to include any form of publication.

Basic inclusion criteria were: Studies investigating postural sway by means of COP excursions in symptomatic or asymptomatic individuals on a forceplate following some form of manual therapeutic intervention. We excluded studies employing dynamic task conditions such as one-leg hopping, walking or any form of translation of the force platform.

To identify all potentially relevant search terms, a comprehensive search strategy was used. The terms were categorized into specific search phases and subsequently combined by using Boolean terms. This search strategy was applied to seven different electronic databases: PubMed, MEDLINE, EMBASE, Web of Science, ScienceDirect, Digital Dissertation and the Cochrane library. The date range of publications searched was from January 1980 to May 2011.
A hand search was conducted and included a review of references cited in studies selected from the original online search. Citation searches of relevant studies were conducted using the PubMed, MEDLINE and ScienceDirect databases.

5.3. Results

5.3.1. Study selection

The database search strategy initially identified 365 studies of which abstracts were screened. The application of inclusion and exclusion criteria eliminated 352 papers. From the titles and abstracts of papers selected \( (n=13) \), full papers were reviewed and 5 studies were finally included in this review. Of these, three were published in peer-reviewed journals [233-235], one of them as a single case study [234]. The remaining studies were under-graduate student projects (Figure 5.1).

Figure 5.1. Flowchart of papers
5.3.2. Characteristics of participants

Apart from the case study [234], all others used small mixed gender groups of 17 [233] to 42 [236] participants. The age groups ranged from 22.5 (SD 5.7) [236] to 74.5 (SD 9.6) [233] years. There were general shortfalls in the documentation of participant health status and demographics. Only two studies enrolled symptomatic individuals with neck pain [234, 235] (Table 5.1).

### Table 5.1: Participant demographics and health status

<table>
<thead>
<tr>
<th>Study</th>
<th>Participant status</th>
<th>Gender (n)</th>
<th>Age in years Mean (SD)</th>
<th>Weight in kg Mean (SD)</th>
<th>Height in cm Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Persson et al. [235]</td>
<td>Cx root compression physiotherapy healthy</td>
<td>14 Female, 10 Male</td>
<td>47 (8)</td>
<td>75 (16)</td>
<td>171 (2)</td>
</tr>
<tr>
<td>Lafond et al. [234]</td>
<td>chronic neck pain healthy</td>
<td>1 Female, 0 Male</td>
<td>45</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jones [236]</td>
<td>healthy</td>
<td>23 Female, 19 Male</td>
<td>22.5 (5.7)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vaillant et al. [233]</td>
<td>healthy</td>
<td>0 Female, 17 Male</td>
<td>74.5 (9.6)</td>
<td>73.2 (12.3)</td>
<td>165.6 (9.3)</td>
</tr>
<tr>
<td>Nolan [237]</td>
<td>unclear</td>
<td>12 Female, 10 Male</td>
<td>18-45</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Cx: cervical
- : not described

5.3.3. Changes in COP associated with manual therapeutic interventions

With one exception [237], all of the studies used combinations of different forms of manual therapeutic and/or exercise interventions. A comprehensive overview about procedures and results is presented in Table 5.2.

In the study by Jones [236], a single osteopathic high velocity, low amplitude (HVLA) manipulation was targeted to the lumbar region between L1 and L5, depending on the physical
examination findings. Furthermore, muscle energy technique was included and involved three repetitions of seven isometric contractions and soft tissue techniques were applied bilaterally to the lumbar paraspinal musculature for 45sec. While a significant, immediate reduction in post-intervention mVel was noted in tandem stance with both eyes open \((p=.003)\) and eyes closed \((p=0.001)\), no differences were observed in normal or unipedal stance under either visual condition.

Persson et al. [235] specifically excluded chiropractic spinal manipulative therapy (SMT) as an intervention for their group of neck pain sufferers instead 15 applications of therapeutic massage to the neck area and exercise sessions over a 3 month period were applied. No significant post-treatment changes in COP sway were identified and no significant reduction in the perceived pain intensity as assessed by VAS occurred.

The intervention program set up by Lafond et al. [234] for their single case study was very diverse and involved HVLA manipulation to the cervical spine in combination with different forms of physical rehabilitation and exercise. A significant reduction in postural sway post-intervention was noted for all included parameters. Mean sway velocity, for example, decreased by 44.1\% \((\text{AP, eyes open})\) to 50.5\% \((\text{ML, eyes open})\) after 16 interventions over 8 weeks. The reduction in COP excursions was accompanied by a decrease in pain perception from VAS 60 to 20.

Vaillant et al. [233] conducted manual mobilizations of the feet in all planes. Before and after the therapeutic manipulation, the participants exhibited very similar COP displacements with eyes open. With eyes closed, a decrease in postural sway was observed particularly in ML direction. However, this difference remained non-significant.
Finally, Nolan [237] used the Stability Index (SI) to investigate the immediate effect of cervical HVLA manipulation on postural sway in asymptomatic individuals. The SI represents the variance of the force platform displacement in degrees from a level position in all positions. Greater amounts of body movements are associated with increasing SI values [238]. A significant reduction in post-intervention SI magnitude was noted in the intervention group in both AP and ML direction while the results of the placebo group remained fairly constant.
### Table 5.2: Alterations in COP excursions associated with a therapeutic intervention

<table>
<thead>
<tr>
<th>Study</th>
<th>Intervention</th>
<th>Experimental setup</th>
<th>Condition</th>
<th>Postural sway</th>
<th>Pain perception</th>
</tr>
</thead>
</table>
| Persson et al. [235] | Physiotherapy  
15x e.g. exercise, massage                                                   | Sampling duration (sec) 10  
Number of repetitions 1  
COP parameter mVel (mm/s) narrow stance  
EO/F | Pre-intervention 11.4  
Post-intervention 12.9  
EO/F | Pre-intervention 47 (8) VAS  
Post-intervention 39 (29) VAS |
| Lafond et al. [234] | Spinal manipulation  
16x cervical (HVLA) C2/3 level  
Rehabilitation  
16x strengthening  
16x ecomotor exercise  
16x balance exercise  
16x stretching | Sampling duration (sec) 30  
Number of repetitions 1  
mVel AP (mm/s) narrow stance  
EO/F  
mVel ML (mm/s) narrow stance  
EO/F  
area (mm²) narrow stance  
EO/F | Pre-intervention -10.0  
Post-intervention -5.5  
EO/F | Pre-intervention 60 (VAS)  
Post-intervention 20 (VAS) |
| Jones [230] | 1x Spinal manipulation  
Lumbar (HVLA)  
1x Muscle energy technique  
1x Myofascial technique | Sampling duration (sec) unclear  
Number of repetitions unclear  
mVel (mm/s) normal stance  
EO/F | Post-intervention 5.7 (2.7)  
EO/F | N/A  
N/A |
| Vaillant et al. [233] | Mobilization  
1x ankle/feet  
Massage  
1x ankle/feet | Sampling duration (sec) EO: 4  
EC: 8  
Number of repetitions 6  
COP parameter displacement AP (mm) narrow stance  
EO/F  
displacement ML (mm) narrow stance  
EO/F | Post-intervention 36  
EO/F  
EO/F | N/A  
N/A |
| Nolan [237] | Manipulation  
1x cervical (HVLA) C0/1, C1/2 level | Sampling duration (sec) 60  
Number of repetitions 2  
COP parameter stability index normal stance  
EO/F | Post-intervention 2.90  
EO/F | N/A  
N/A |

* = The results presented have been extracted from charts. Results are presented as Mean (SD)
Levels of significance compared to baseline. * p≤0.05, ** p≤0.01, *** p≤0.001
- : not described
AP: antero-posterior, C: compliant (foam) surface, EC: eyes closed, EO: eyes open, F: firm surface, HVLA: high velocity low amplitude, ML: medial-lateral, mVel: mean velocity, N/A: not applicable
5.4. Discussion

The conduct of large scale studies investigating changes in COP excursions associated with manipulative therapy has been announced at scientific conferences [239]. COP measures have also been specifically suggested as a monitoring tool for chiropractic practice [218]. This, however, is premature. So far only a few studies have been consequently reported and two of these were under-graduate theses [236, 237] that have not been additionally published in a peer reviewed journal.

COP measures are used by practitioners applying manual therapies, so the lack of good quality studies may suggest that publication bias has a role. This refers to the tendency on the part of authors to submit, as well as the reviewers and editors, to accept manuscripts based on the study findings [240] as the strongest and most positive studies are most likely to be published [241].

Limitations in some of the included studies were the absence of a comparison or control groups [233, 234, 236] and the generally small samples sizes. Where multimodal interventions were used [234, 235], the effectiveness of particular treatments remains unclear. Where changes in postural sway were reported [233, 242], it was not possible to determine whether the intervention itself or learning effects due to repetitive testing [109] were the causative factors.

The reliability of the experimental setups is another point of concern as all included studies employed very short sampling durations between 4sec [233] and 30sec [234]. Although Vaillant et al. [233] used six repetitions, the combined sampling duration of 50sec was still very short (Table 5.2). The expected reliability of the data presented in this review is therefore low and may well have adversely affected the results as discussed in Chapter 2.
In addition, any interpretation of the reported results is severely limited by the rather poor overall quality of methods, study design and/or documentation. However, it appears that when healthy participants were tested, generally no significant change in postural sway between COP excursions pre- and post-intervention was noted [233, 242]. When Nolan reported a significant decrease in postural sway associated with cervical SMT [237] this may be explained by the fact that the Biodex Balance System was the only forceplate allowing surface perturbation and a sway degree based COP parameter was employed.

With regards to the study by Persson et al, there is no conclusive evidence that massage is an effective treatment for cervical nerve root compression [243]. This may at least partly explain why the perceived pain levels did not decrease significantly and, should a correlation between these two factors exists, the COP excursions remained similar to pre-intervention stage.

With open eyes, the results reported by Vaillant et al. [233] further indicate that the mobilization intervention either had no immediate effect on postural sway if visual fixation was allowed. This may have largely compensated for the presumed benefits of the mobilization procedure as underlined by the decrease in COP displacement under visual deprivation.

Based on the literature available, there is no sound evidence that manual therapeutic interventions may exhibit any effect on body sway, at least in asymptomatic participants. There is weak evidence that a significant decrease in pain perception in symptomatic individuals was associated with decreasing COP excursions [234], while at similar pain perception, postural sway remained unchanged [235]. This does not necessarily indicate an effect of the therapeutic intervention itself. If pain reduction is the underlying mechanism behind the decreasing postural sway, then analgesics or natural cause may have contributed substantially to altering COP excursions. However, the low quality of the respective studies does not encourage further hypothesizing at this point.
5.4. Conclusion

Due to the heterogeneous study designs there is no sound scientific evidence that manual therapeutic interventions may exhibit any immediate or long-term effect on COP excursions in either healthy or symptomatic individuals. Indeed any changes may simply be due to a decrease in pain. If further research is contemplated it should be implemented with a standardized testing protocol to allow for inter-study comparison, control groups and larger sample sizes.
COMPREHENSIVE METHODOLOGY FOR PILOT AND PROSPECTIVE STUDIES
CHAPTER 6

Comprehensive methodology for pilot and prospective studies

In this chapter, the general methodology and equipment of both pilot and prospective study will be described in detail. Any deviation or modification associated with specific requirements of a study is outlined in the respective chapter section.

6.1. Material

As described before, the Metitur Good Balance GB300 System® CE (Metitur Oy, Finland), a strain gauge based force platform with three force transducers was used to conduct our experiments (Chapter 1).

The force platform was connected to a computer through a three-channel amplifier and an analogue-to-digital (A/D) converter. The system uses a combination of two different filters for data processing. First, a median filter with a window length of seven data points will be used to reduce impulse noise. Secondly, high frequency noise from both the measuring equipment and the A/D conversion is reduced by a low-pass filter with a cut-off frequency of 10Hz. The force transducers are situated at the corners of the equilateral triangular platform and vertical forces are registered. On the basis of the force signals from each corner, the system calculates the x (medio-lateral, ML) and y (antero-posterior, AP) coordinates of the COP affecting the platform.
The Good Balance software provided with the system was installed on a laptop PC (AMILO Pi 2550 Notebook PC. Operating system: Windows Vista Premium®, Microsoft Corporation) and was used to process the data from measurements of total body sway.

6.2. Recruitment of participants, patient information and declaration of consent

6.2.1. Patient recruitment procedures

All procedures involved in any part of this thesis have been approved by the Murdoch University Ethics Committee with Approvals no. 2010/066 and 2010/173 (Appendices 1 and 2).

The potential participants were patients of the Praxis für Chiropraktik, Wolfsburg, Germany. For new patients, the first contact was made over the phone where the patients were informed about the conduct of the trials. Current patients have been contacted by phone prior to their next appointment or during a visit. The contact was initially made by clinic reception staff. For this purpose, five front desk reception staff were trained to provide initial participant information and answer common questions prior to the beginning of the study.

At first contact, the clinic staff gave the following general initial information about the experiment via phone using the following script (in German):

"Momentan wird in unserer Praxis eine Forschungsstudie durchgeführt, die eine Untersuchung der Körperbalance beinhaltet. Dazu ist es erforderlich, auf einer Druckmess-Plattform mit geschlossenen Augen zu stehen. Zusammen mit einer begleitenden, eingehenden Untersuchung wird dies ungefähr 45min dauern. Sollten Sie mit einer Teilnahme einverstanden sein, wäre es erforderlich, an zwei ungefähr 5 Minuten dauernden
Folgemessungen teilzunehmen, die sich an Ihre normalen Behandlungstermine anschließen würden. Dürfen wir Ihnen Informationsmaterial zu dieser Studie zusenden?"

[In English: “At present a research project involving balance assessment is being conducted at our clinic. It requires standing on a measuring platform four times for the duration of about one minute with both eyes open and closed. The total time involvement will be about 45 minutes to 1 hour including a physical examination, your health history and the recording session itself. If you agree to participate you will be required to commit for 2 follow up visits, but these will be less time consuming (approximately 20 minutes) and are where possible arranged along with your normal treatment appointments. Can we send you some information about this research?”]

If the person agreed, an information letter specific to the study in question (Appendices 3-4 and 10-11) and a consent form (Appendices 5 and 12) were sent to them for perusal.

The receptionist did also advise the following (in German):

"Wenn Sie die Informationen gelesen haben und zu einer Teilnahme bereit sind, unterschreiben Sie bitte die beigefügte Einverständniserklärung und bringen Sie zu Ihrem nächsten Termin mit. Sollten Sie irgende welche Fragen haben, kontaktieren Sie vor Ihrer Unterschrift bitte die Praxis."

[In English: “Once you have read the information and if you decide to participate please sign the consent form and bring it with you on your next visit. If you have any questions please contact the writer before signing the consent document.”]
Care was taken to familiarize all staff with the protocol so standardized initial information could be provided. As a preparation, the training of the individuals involved also included practice calls.

6.2.2. Information letter for potential participants

In addition to the initial oral information, further detailed information on the methodology and other aspects of the research were provided. These information letters were made available in both German and English versions. In addition, there were different versions for a) the reliability pilot study (not incorporating follow-ups and references to patient related issues) and b) the feasibility pilot study and the prospective study (Appendices 3-4 and 10-11).

The points addressed included the aims and purpose of the trial including the full title of the experiment, the practical arrangements and procedures, the expected time involvement as well as statements regarding the patient’s rights and confidentiality. Furthermore, the necessity of two follow-ups was explained and any involvement of commercial or non-commercial sponsors as well as any financial reimbursement or remuneration for the trial participants declined. In addition, the information sheet contained contact details in case a participant required further information during the course of the trial as well as contact details of institution’s Ethics Committee should a participant want to file a complaint for any reason.

Possible benefits of the research were also outlined. For the individual, this included the identification of impairments in postural control and the potential application of the collected data in fall or injury prevention and rehabilitation. Establishing baseline values and reference data for various pathological conditions targeted were considered in the interest of scientific progress in the area of postural control research.
Another point addressed was the possible risks and inconveniences associated with participation. Specifically, the participant was informed about the possibility that in rare circumstances he/she may lose balance and fall. In addition, the possibility could not be ruled out that standing with visual obstruction may provoke fear in certain individuals.

Finally, a statement was included that the person did not have to participate in this observational study to remain a patient of the clinic and that there were no ramifications should they choose not to participate. They were also informed that they may change their mind and withdraw from the trial at any stage and without consequence.

To ensure that the written information was easy to understand for a lay person, the form was read by three individuals of different ages that are non-medically trained and not involved in the trial. This written information sheets was distributed by the clinic staff after an interest in participation is declared and was send by mail/fax or distributed in clinic.

6.2.3. Cross-cultural translation

The translation from German into English language was conducted by an England-trained psychiatrist. That draft was again translated back into German by a third person (a chiropractic colleague not involved in the research) that concluded that the original and translated versions were identical. The final draft was once more checked for fluent language.
6.2.4. Patient's rights

All individuals involved in the research project were fully informed about their rights and in particular as patients at the clinic. This included the right to refuse parts of the physical examination procedures that were solely related to the research project. The patient was further entitled to a summary of the research outcome and to be informed about his/her own performance immediately after the recording session.

As already outlined in Section 6.2.2, the patient had the right to withdraw consent and discontinue his/her participation in the study at any stage or request the ending a recording session without giving reasons. In this case, it was ensured that discontinuing the trial would not have any ramifications for the patient, especially with regards to the continuation and quality of care at the clinic. No attempt was made to persuade the patient to resume participation.

6.2.5. Complaints procedures

The participants were informed about their right to file a complaint about any aspect of the conduction of the study. In this case, the relevant Ethics committees was to be notified of any adverse event.

In addition, a report was to be filed by the chiropractor involved to the ethics committee of the German Chiropractors’ Association (DCG) as required of members by the statutes of the DCG. All four chiropractors at the clinic are members of the DCG and are required to adhere to a Code of Ethics. The DCG does not have an ethics committee constituted for the purpose of approving research but instead acts on any complaints made by the public about a member.
To this extent the authority of the DCG is limited to expulsion of members. Full records of the potential incident(s) that have led to the complaint as well as records of all relevant communications will be maintained and provided to the institutions if requested and with the permission of the participant.

6.2.6. Confidentiality

All data gathered was handled with full confidentiality. To ensure this, all participants were allocated a personal ID number. This individual ID code was a consecutive number preceded by an “PS” for new patients without previous treatment and symptomatic current patients that are recorded after at least 4 month absence. In addition, "PC" was allocated to healthy participants of the control group and the reliability pilot study.

Apart from the consent form, the participants can be identified by this ID number only; no connection between results from the COP recordings and names is possible. No data was or will be accessible to any person not authorized and directly involved with the study or be disclosed to any third party or institution unless required by law. Data is kept in a password protected computer owned by the on-site student investigator (AR) and the paperwork is stored in a locked metal cabinet at the clinic.

For clinical use and patient management outside this research, the case history and relevant examination findings were transferred with the patient’s name as necessary. In this case, the identification of the patient is possible but as the ID number was erased for data usage in clinic, the name cannot be correlated to COP measures gathered during the trial.
6.2.7. Obtaining consent

Four qualified chiropractors (AR, TB, AS, DT) administered consent. The principal investigator (AR) confirmed the procedure and ensured that consent has been obtained in accordance with the outlines stated above. The original consent form (Appendices 5 and 12) was filed and stored separately from the patient's physical examination findings, medical history and trial results so no identification of the individual was possible at a later stage. After giving consent, the participant was provided with a copy of the consent form.

6.3. General procedures

6.3.1. Location and positioning of equipment

The Metitur system was centrally located in an otherwise unused room in the Praxis fuer Chiropraktik, Wolfsburg. The computer used to store the data recordings was positioned in a way that the participant was unable to visually assess their own performance during the trial. The test conditions (light, room temperature) were standardized prior to the tests; this is expected to at least partially compensate for recordings at varying times of the day. Noise control ensured that no audible distractions occurred. The experimental setup within the location is shown in Figure 6.1.
6.3.2. Calibration process

The calibration of the force platform was checked weekly. In addition, the force platform performed a self-test for the basic levels every time the computer program is opened. In addition, the self-test was done automatically during the day at 2-hour intervals.

If necessary, a re-calibration with a certified 10-kg weight was performed as outlined in the user’s manual [94] at the latest after a week of usage.

6.3.3. Safety and on-site assistance

Various measures were taken to ensure patient safety. Prior to the measurements, the Metitur Good Balance 300 System® CE was equipped with a safety handle which remained attached for all measurement sessions. The patient were made familiar with it prior to the trials. From a
technical perspective, the system itself fulfils the standards governing electric medical instruments for user and patient safety (EN 60601-1) and electromagnetic compatibility (EN 60601-1-2, 1993 and EN 55011, 1991), holds the Medical CE certificate (NB ID 0537) and FDA certificate (USA) and is a Certified Quality System (ISO 9002).

The surrounding of the measuring device was cleared of obstacles (in any direction not covered by the safety handles) that may cause injury if loss of balance occurred. The investigator provided assistance to any participant on the force platform irrespective of gender or age. For the duration of the recording, the examiner and/or an assistant was to be positioned in such a way that immediate support to the participant was possible if excessive sway occurred or help was requested.

6.3.4. Emergency medical care

In the unlikely event of an accident or emergency, first aid equipment was located in the room where the experiments take place and all examiners and clinic staff hold valid first aid certificates. If a fall resulted in serious physical injury and after first aid has been provided in the clinic, follow-up medical care is ensured by a radiologist (Jürgen Flimm MD, PhD) and a general practitioner (Martin Buhr, MD, PhD) both of whom have agreed to provide priority care. If these doctors were not available or the injury is too severe to move the participant we were to arrange for an ambulance to transport the person to a hospital emergency department.
6.3.5. Adverse incidents reporting

In the event of an adverse incident or event, a complete record of the incident itself as well as all relevant conversations were to be maintained and forwarded to the relevant institutions. In case a participant experienced fear, enough time were allowed to talk it through, should the patient wish to do so. Thereafter, no pressure was applied to resume the participation unless the patient him/herself decided to continue.

If the adverse incident was suspected to be related to aspects of the experimental setup, the trial was to be stopped until this possibility was investigated and the procedures, if necessary, changed in order to avoid similar incidents. In this case an ethics amendment was to be sought.

6.3.6. Data storage and safety

All the data relating to the pilot and prospective study remain stored to allow reference for at least five (5) years. It was initially stored on the hard drive of the password-locked mobile computer owned by Alexander Ruhe (AR) while safety copies were made at least twice a week on equally password-locked external hard drives and/or on DVD/CD. Each week data was transferred to Dr Bruce Walker’s (BW) office by encrypted email.

The original data in any format were safely locked away in clinic. It was inaccessible to anybody but authorized personnel. Only the primary investigators (AR, TB, AS) had access to the data with individual passwords that allow a tracking of access.
The access was restricted to purposes directly associated with the research project and was only allowed within the individual's area of responsibility. Only AR as principal researcher and BW as principal supervisor had unrestricted access. BW carried the overall responsibility for the data handling and safety.

After 5 years, the digital data (CD/DVD) will be disposed of by shredding the discs, all paper documents will be similarly destroyed with a document shredder.

6.4. Experimental procedures

6.4.1. Flow of examination and recordings

The COP measures (but not the survey instrument) were conducted prior to the examination. The rationale for this was to avoid a potential effect of the physical examination procedures on the measurements (e.g. because of pain provocation or the mobilizing effect of orthopedic testing). In addition, the patients received a focused examination depending on their presenting complaint; therefore any effect of an examination procedure was not uniform throughout the participants.

Unless the patient stated otherwise, it was assumed that the participant was able to stand for the period of 90 sec per recording as the physical demand for this duration was not expected to exceed tolerance even under pain and endanger the participant or aggravate his/her complaint.

Prior to the measurements, the participant was asked about any pain presence. If there was pain, he/she was asked to locate it and rate the intensity on an 11-box numeric rating scale (NRS-11) before stepping on the force platform.
As the time to fill out the questionnaire was expected to vary greatly between individuals, this part concluded the procedure to avoid delays and allow sufficient time for detailed answers. Accordingly, the procedures were conducted in the following order:

a) Information  
b) Questions (optional)  
c) Obtaining consent  
d) Questionnaire(s)  
e) Assessment of pain presence and intensity  
f) COP measurement  
g) Physical examination  
h) Intervention

### 6.4.2. Health questionnaire

The participants were asked to fill out a questionnaire prior to the physical examination (Appendices 7 and 13). This health questionnaire consisted of various questions covering different areas such as a general health history, patient demographics (age, gender), questions regarding any present or previous conditions that might have or has affected balance (vestibular, neurological, traumatic, vascular or eye sight), as well as a history of any surgery or traumatic incidents such as an Road Traffic Accident (RTA). In case of an RTA, further questions regarding speed and direction of impact or relative head position were asked.

The use of medication were investigated (current history of medications, type) to assess their possible effect on postural stability such as induced by neurological or vestibular impairment. With regard to pain or functional impairment itself, questions were asked regarding location,
duration, intensity, history of this intensity and location as well as the number of previous episodes. The pain intensity was assessed by means of a 11-box numeric rating scale (NRS-11). It is easy to administer and score, has good evidence for construct validity and reliability [244, 245], the compliance rate with the measure is high and the scores can be treated as ratio data (Figure 6.2).

**Figure 6.2**: Numeric pain scale (NRS-11)

![Numeric pain scale (NRS-11)](image)

Select the number that best describes your current pain intensity
(circle one number only)

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>No pain</td>
<td>Moderate pain</td>
<td>Worst possible pain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For the follow-up appointments, a questionnaire only assessing pain intensity (NRS-11) and disability (DRI) will be handed out (Appendices 9 and 15).

**6.4.3. Disability Assessment**

The perceived disability was addressed by the Disability Rating Index (DRI), a questionnaire found to be both valid and reliable [246] (Appendices 8 and 14).
6.4.3.1. The Disability Rating Index

The DRI was chosen for its simplicity as well its suitability for a comprehensive disability assessment of both spine and extremities. Although a German version was not available, the simplicity of the VAS-based questionnaire facilitated the translation and cultural adaptation. It is therefore expected that the validity of the original is retained.

The DRI had to be modified slightly. As the German translation of the DRI (2) requires more words and thereby space compared to the original version (1), the text had to be subdivided in two lines. When testing the translated DRI with individuals unfamiliar with it, there was a strong tendency to mark the line right in the center of the statement deemed most appropriate below, sometimes they were even circled. It was therefore decided to leave the additional explanatory text out (3) as it was considered both leading and confusing (Figure 6.3).
Figure 6.3: Original, translated and modified DRI

To compensate for this, a cover page with examples of filled out rating scales with the original (translated) text was included whenever the DRI was distributed (Appendix 9 and 15). The responses by a convenience sample of participants (n=10) confirmed that this version was more readily understood and correctly filled out.

6.4.3.2. Translation process

The translation process was conducted as described in Section 6.2.3. A German version of DRI, previously translated by a local, England-trained clinical psychiatrist (FS), was used with
the consent of the author. This translated version was independently reviewed and back-translated into English by an independent native British (UZ), who was blinded to the original English version of the DRI. This translator is proficient in both English and German, and holds a Masters degree equivalent in Linguistic Studies.

The back-translated version was then compared with the original English version and any inconsistency in the German version was corrected. Both versions were identical.

The initial agreement about the German version was also excellent with only two discrepancies involving a synonym and a different order of words respectively. While FW suggested "Vornübergebeugt am Waschbecken stehen" [English: Standing bend over a sink] as the most appropriate translation, UZ preferred the slightly modified order "Über das Waschbecken gebeugt stehen". After a brief discussion it was decided to use the latter version as it was considered the easiest to grasp.

Secondly, UZ used the literal translation for Section 11 of the health questionnaire into "Heben schwerer Objekte" [English: Lifting heavy objects] while FW used a synonym and recommended "Heben schwerer Gegenstände". It was decided to follow FW’s suggestion as while there are two equivalent words for "objects" in German language, "Gegenstände" is the more colloquially used one in this context.

Content validity of each item was evaluated by subjecting the two versions to critical appraisal by two bilingual chiropractors (AS and TB) for semantic equivalence, clarity, and grammatical accuracy. No corrections were recommended.
6.4.4. Physical examination

The purpose of the physical examination was the identification of neurological, biomechanical or other health related deficits that may influence postural stability, to allow for a statistical analysis as well as to guide a possible therapeutic intervention.

For examination, the participant was asked to undress to their underwear. Although it is not culturally practiced in Germany, gowning was offered to all participants. All findings were recorded in appropriate detail on an examination sheet (Appendix 6), marked with the participant’s individual ID number.

During the physical examination, measurements of height and weight were undertaken. The weight was assessed by the Metitur system that has been previously calibrated by certified weights. Based on height and weight, the Body Mass Index (BMI) was automatically calculated for each participant [247]. The focus of the examination was on spine and lower extremities as no effect of the upper extremities on balance performance has been demonstrated.

6.4.5. Range of motion

Range of motion (ROM) refers to the area through which a joint may normally be freely and painlessly moved [248]. With regards to the assessment of ROM, the reliable and valid allocation of specific degrees is often only achieved by computerized motion analysis devices unavailable to us.

As “normal” motion is individually different due to gender or age differences [249], unequal ROM (greater than 30% difference) between the two sides was regarded as an indicator of
restrictions. The ROM analysis was also assessed in all regions by subdividing the findings into three categories:

a) normal (0-30%)

b) moderate restriction (30-50%)

c) marked restriction (>50%)

The ROM was assessed for cervical, thoracic and lumbar spine by active and passive motion in rotation, flexion/extension and lateral flexion. For the hip joint, internal and external rotation was recorded, as was internal/external rotation, flexion/extension and translation for knee and ankle joints. There was no attempt to locate spinal levels of notional small joint restrictions due to the lack of reliable and valid procedures available [250].

The procedure for the ROM assessment for the different areas was as follows:

**Cervical spine:**
Active ROM was tested with the patient sitting upright. The participant was asked to "look over his/her shoulder" to either side as far as he/she could. Following that the instruction was to look "down to the floor" and "up to the ceiling" as far as possible. The same movements were repeated passively. The chiropractor thereby took hold of the head and gently moved it through the motions while the participant was asked to relax his/her muscles completely.

**Lumbar spine:**
Active and passive lumbar ROM was tested with the patient sitting upright. With arms crossed, the participant was asked to rotate to either side as far as he/she could. The same movements were repeated passively with the chiropractor rotating the patient. Flexion and extension was
assessed in a similar way by bending forward and arching backwards. Care was taken to ensure that the movement was primarily initiated in the spine and not at the hip joints.

**Hip:**

Hip ROM was evaluated in active and passive motion. The patient was asked to move the hip on one side in flexion, extension, adduction and abduction while standing on the other leg with hand support for stability. The movements were repeated passively while standing (extension) and lying supine (flexion, abduction, adduction). Hip rotation assessment was conducted passively. With the patient supine, both hip and knee were flexed to 90°. While contacting knee and ankle, the hip was internally and externally rotated until the motion induced movement of the pelvis on the bench.

**Knee:**

With the patient lying supine, the participant was asked to actively move each knee through flexion and extension. The patient then relaxed the muscles in the leg allowing the examiner to passively flex and extend the knee through the available range. With the hips flexed to 90°, the internal and external rotation of the knee joint was assessed.

**Ankle:**

The examiner instructed the patient to actively move the ankle as far as they can into plantarflexion, dorsiflexion, eversion and inversion. Following that, the patient was asked to relax and the procedure was repeated passively.
6.4.6. Joint and soft tissue palpation

As inter-examiner reliability of passive assessment of segmental intervertebral motion in the cervical and lumbar spine by manual practitioners is low, it was not included to identify joint dysfunctions [251]. Instead, palpation for pain in the different regions was used as an indicator for joint restrictions as it has been shown to be reproducible at a clinically acceptable level, both within the same examiner and among examiners [252]. The same has been shown for the examination of the thoracic spine for musculoskeletal pain [253].

6.4.7. Orthopedic tests

There are numerous issues with the evaluation of the validity of palpatory procedures and pain provocation tests in physical assessment, especially as there are often no agreed upon “gold standards”. Depending on the patient's presenting complaint(s), the following orthopedic tests were performed for the different regions:

6.4.7.1. Cervical spine

Examination of the cervical area included the Spurling's test for nerve root involvement as it has a sensitivity of 92% and specificity of 95% with positive predictive value (PPV) of 96.4% and negative predictive value (NPV) of 90.9%. It is used in predicting a diagnosis of a soft lateral cervical disc prolapse with resulting nerve root compression [254, 255]. In addition, cervical distraction was tested as it has also been shown to have high specificity (0.97, SD 0.85-1.0) and a fair sensitivity of 0.44 (SD 0.14-0.79) for cervical radiculopathy [256]. The
upper limb nerve tension test (Elvey) was also performed as they can be used to rule out this diagnosis due to their high sensitivity (0.97, SD 0.90-1.0) [257].

Spurling's Test
The participant were seated comfortably. From behind, the investigator interlocked the fingers and rested both hands on top of the patient's head. The examiner laterally flexed the patient's neck approximately 30 degrees to either side and then applied a downward axial compression making sure not to laterally flex the patient's neck any further. This position was maintained for at least 30 seconds. The test was considered positive if pain or paraesthesia are reproduced [256].

Cervical distraction
The investigator gently took hold of the head with both hands and applied upward axial traction. A positive result was a decrease in pain and/or radicular symptoms [256].

Nerve tension test (Brachial plexus tension test of Elvey) [256]
First, the shoulder girdle was gently depressed. The arm was then positioned in shoulder abduction (approximately 110 degrees) and external rotation, forearm supination, wrist extension and finger extension. The range of elbow extension was then carefully assessed and the subjective response to testing noted. The test was positive if the pain is reproduced, the side-to-side difference in elbow extension exceeds 10° or if contralateral cervical side bending increased symptoms while ipsilateral side bending lead to a decrease [256].
6.4.7.2. Lumbar spine and sacroiliac joint

Specific tests for the lumbar spine to identify pain or manipulative lesions have not shown sufficient validity [257]. Motion tests of the SI joint often demonstrate larger movements than can be attributed to the motion, probably due to soft tissue gliding. After several studies with inconclusive or conflicting results [258], a recent study investigating the reliability of motion- and pain provocation tests for the sacroiliac (SI) joint concluded that a combination of three out of five tests should be employed for acceptable reliability [259].

The Straight Leg Raise (SLR) was performed as it has been shown to be a valid and reliable test when assessing the severity of lumbo-pelvic pain [260] although its specificity in diagnosing lumbar disc pathologies remains questionable [261, 262].

From the relevant literature we used a protocol to test different aspects of the SI joint consisting of SLR [260], joint and soft-tissue palpation, hip internal/external rotation, Gaenslen's and Gillet's [263] as well as Partick-Faber's [259, 264, 265] in modification of a test series originally proposed by Cattley et al. [266].

The orthopedic tests listed above were conducted as follows:

**Gaenslen's Test**

The patient was asked to lie supine on the edge of a table. The leg being tested was hyperextended at the hip so that it hung over the table. The other leg was flexed at the hip and knee. The patient was instructed to hold the non-tested leg with both arms while the chiropractor stabilized the pelvis and applied passive pressure to the tested leg to held it in the hyperextended position. The examiner then applied additional pressure to place the hip into a
position of further extension and adduction. A positive test was noted if pain was provoked or reproduced [248].

**Gillet's Test**

The participant was asked to stand while the examiner palpated the PSIS with one thumb and the sacrum with the other thumb staying parallel to the first thumb. The patient was instructed to stand on one leg while pulling the opposite knee up toward the chest. A positive test was noted when the posterior superior iliac spine (PSIS) on the ipsilateral side of flexed knee did not move or moved minimally in the inferior direction. The PSIS on the side of hip flexion should move slightly anterior [248].

**Patrick’s Faber Test**

With the patient lying supine, the patient's hip was brought into a position of flexion and abduction. While stabilizing the opposite side of the pelvis, an external rotation and posteriorly directed force was then applied to the ipsilateral knee. A test was considered positive if the patient's pain was reproduced [248].

**Straight leg raise (SLR)**

The SLR was conducted both actively [265] and passively [260]. The test was performed passively first. The investigator gently lifted up the leg with the knee extended while the patient was lying supine. The examiner continued to lift the patient's leg by flexing at the hip until pain was elicited or end range was reached [248]. The patient was then asked to lift the leg actively by flexing the hip with the knee extended. A positive finding for a neurological cause was noted if pain was reproduced in the leg and low back between 30-70 degrees of hip flexion. It may also indicate a lumbar disc herniation at the L4-S1 nerve roots [261, 267].
6.4.8. Neurological tests

The neurological test included the assessment of myotomal strength of the lower (L3-S1) and upper (C3-T1) extremities, a procedure that has shown good inter-examiner reliability ($k=0.57-0.82$) [268]. The muscle testing were graded 0-5 according to the following definitions:

0/5: No muscle movement
1/5: Visible muscle movement, but no movement at the joint
2/5: Movement at the joint, but not against gravity
3/5: Movement against gravity, but not against added resistance
4/5: Movement against resistance, but less than normal
5/5: Normal strength

The manual muscle testing involved the common procedures and major muscle groups [269]. Furthermore, the reflexes of C5-7 (upper extremities) and L4,S1 (lower extremities) were assessed. The grading was on a similar scale of 0-5:

0: No reflexes
1: Less than normal
2: Normal
3: More brisk than normal
4: Brisk
6.4.9. Intervention

Following the COP measurement, a therapeutic intervention targeted at the patient’s complaint was administered. The treatment was standard chiropractic care which consisted of one or more of the following:

a) Manipulation of spine or extremities
b) Mobilization of spine or extremities
c) Soft tissue techniques such as Post-isometric Relaxation [270]
   or Active Release Technique [271]

The techniques above can be defined as follows:

Manipulation
Manipulation of spine or extremities refers to the hands applied to the patient, incorporating the use of instructions and maneuvers and the application of a load (force) to specific body tissues with therapeutic intent. During spinal manipulation, the practitioner delivers a dynamic thrust (impulse) to a specific vertebra or joint. The clinician controls the velocity, magnitude and direction of the impulse [272]. Hereby, the art of spinal manipulation lies in the clinician’s ability to control these three factors once the specific contact with a vertebra is made [273].

Mobilization
Spinal or extremity mobilization is a type of passive movement of a joint or region. It is performed with the aim of achieving a therapeutic effect by increasing or facilitating the range of motion of that joint or region. Mobilization involves low velocity, either small or large amplitude oscillatory movements applied anywhere in a range of movement [274].
Post-isometric relaxation (PIR)

The post-isometric relaxation technique begins by placing the muscle in a stretched position. Then an isometric contraction is exerted against minimal resistance of about 10-15% of maximal strength. Relaxation and then gentle stretch follow as the muscle releases. This technique is applied to tight and tender muscles that are commonly associated with musculoskeletal pain [270].

Active Release Technique (ART)

This technique involves an initial (passive) shortening of the involved tissue, applying a contact tension with the therapist's fingers and then lengthening the tissue or making it slide relative to the adjacent tissue [271].

6.5. Painful regions

Depending on their main complaint, the participants were subdivided into three groups: Region 1 (head/neck), Region 2 (thoracic area) and Region 3 (lumbar spine and pelvis). The regions were based on those defined by Kourinka et al. in the "Standardised Nordic questionnaires for the analysis of musculoskeletal symptoms" [275]. In modification, the spinal area described as "upper back" was extended to the full thoracic/chest area to include rib and intercostal symptoms.

While this subdivision is based on the most prevalent pain source, an overlap of two or more complaints is possible. In this case, the participant was asked to decide on one main complaint based on pain severity, however, all complaints were comprehensively addressed by the manual intervention (Figure 6.4).
6.6. COP parameters

6.6.1. Mean sway velocity

This is one of the most commonly used COP parameters and is calculated by taking the total distance of the COP path travelled in the respective direction and dividing it by the sampling duration ($T$):

$$ m\text{Vel}_{\text{AP}} = \frac{\sqrt{(x_{\text{AP}(n+1)} - x_{\text{AP}(n)})^2}}{T} $$

$$ m\text{Vel}_{\text{ML}} = \frac{\sqrt{(x_{\text{ML}(n+1)} - x_{\text{ML}(n)})^2}}{T} $$

(6.2)

6.6.2. 90% circle diameter

There is a broad range of parameters describing the area covered by a certain percentage of the COP path during a given time (Figure 6.14). While some used an ellipse because COP...
excursions particularly in symptomatic individuals often have a dominant sway direction, others prefer a circle because the sway in healthy controls is rather equally distributed in ML and AP direction. The reason why Metitur chose the rather unusual circle diameter may be explained by the simple rationale to establish another parameter as a unique selling point.

### 6.5.3. Sway direction

Based on the Metitur parameter "direction of main axis", a coefficient of the angle in degrees, the 360° circle was subdivided into four quadrants. The subdivision into 90° sections may allow to correlate physical examination findings with the main sway direction into anterior (1), right (2), posterior (3) or left (4) direction (Figure 6.5).

**Figure 6.5**: Sway direction quadrants

![Illustration: Alexander Ruhe](image)
In addition, the data was analyzed by dividing the circle into ML and AP direction quadrants to investigate whether there were general differences in sway direction between symptomatic individuals and healthy controls irrespective of the physical examination findings. For this purpose, section 1 and 3 as well as 2 and 4 were combined. Figure 6.6 presents a visual representation of a COP path including the main sway axis and 90% circle.

**Figure 6.6:** Visualization of COP path, main sway axis and 90% circle
SAMPLE SIZE CALCULATIONS, RELIABILITY AND FEASIBILITY OF THE EXPERIMENTAL SETUP
CHAPTER 7

7.1. Intra-session reliability of center of pressure measures in bipedal static stance using the Metitur Good Balance GB300 system

7.1.1. Background

This study aims to identify an appropriate and reliable experimental setup for use in a clinical setting. Based on previous literature review [92] and a feasibility study we tested the best practice setup previously identified therein and described in Chapter 2.

To our knowledge, no reliability study using a best practice setup has been conducted or published for this particular forceplate. We aimed to establish and test procedures that yield reliable data with an optimized ratio between repetitions and trial duration for everyday clinical use.

7.1.2. Methods

7.1.2.1. Participants

We aimed at enrolling ten healthy individuals recruited from a group of recreational athletes. They were initially contacted by their coach/medical personal about the possibility to participate in this study. In case of interest, they were asked to contact the clinic for further details. After oral and printed information had been given, the subjects consented to participate in this study, which was approved by the Murdoch University Human Research Ethics Committee (Approval No. 2010/066).
The cut-off age for the participants was 50 years as after that age related impairments to postural stability could not be excluded [12, 105, 148].

In this study, healthy was defined as the absence of any self-reported neurological or musculoskeletal impairments, pain or disability for a minimum of 6 months prior to the time of evaluation. This specifically excluded individuals with a history of low back pain or previous injury to the neck or lower extremities, any known balance problems, or the usage of medication associated with pain suppression or altering sensory perception.

Prior to the recordings, a physical examination screening was conducted for all participants by an experienced chiropractor (TB) that was otherwise not involved in this study. No relevant biomechanical deficits with regards to joint mobility or muscular function were reported.

7.1.2.2. Material and procedure

The force plate used in this study was a Metitur Good Balance GB300® CE (Metitur Oy, Finland). Signals were sampled at 100Hz, amplified and converted from analogue to digital with a cut-off frequency of 10Hz.

The subjects were asked to remove their shoes and stand upright on the forceplate with their eyes closed, the head erect and their arms hanging loosely by their sides. The foot position was narrow stance with toes and heels touching. For the duration of the recording, the participants were further instructed in German to "stand as still as possible" [276] (Figure 7.1.1).
Five successive trials of 35, 65 and 95 seconds duration each were conducted. The initial 5 sec period was not recorded to allow the participant to adapt to the postural task. Rest periods of 60 sec were provided between each trial during which the participants were allowed to sit down while maintaining their original foot position.

The tests were performed in a quiet room with standardized temperature and lighting. The forceplate was calibrated prior to the recordings and further underwent an automatic calibration check before each trial.

7.1.2.3. Data analysis

Overall, nine COP parameters were calculated from the COP\text{net} of each trial by the software provided to allow for a broad spectrum of sway path analysis. The reliability were calculated
for both the sampling duration and the individual COP parameters in order to identify the most appropriate relationship between the descriptive and discriminative value of the parameters and a sampling duration that does not exceed the patient's tolerance but challenges the balance system enough to allow the assessment of postural sway deficits.

The reliability values of the COP measures for this experimental setup was assessed by computing the Intra-class correlation coefficient (ICC) using a two-way ANOVA model. Derived from these ANOVA results, the ICC$_{2,k}$ described by Shrout et al. [138] was calculated using absolute agreement. It compares the inter-subject with the intra-subject variability and considers random effect over time. In addition, it a frequently reported model in the literature and therefore allows at least limited comparability of results.

The ICC$_{2,k}$ is calculated using the following formula

$$\text{ICC}_{2,k} = \frac{\text{BMS} - \text{EMS}}{\left(\frac{\text{BMS}}{\text{OMS}} + \frac{(\text{OMS} - \text{EMS})}{n - 1}\right)}$$  \hspace{1cm} (7.1)

where BMS is the between-subjects mean square, EMS is the error mean square, k is the number of observations, OMS is the observations mean square, and n is the number of subjects.

The ICCs were interpreted using the following criteria: 0.00-0.39 = poor, 0.40-0.59 = fair, 0.60-0.74 = good and 0.75-1.00 = excellent [277]. The standard error of measurement (SEM) was assessed in conjunction with the ICC$_{2,k}$ values as the latter normalizes measurement error relative to the heterogeneity of the participants [278].
The SEM estimates how repeated measures of the participant tend to be distributed around their unknown “true” score in 68% of the time. An individual's true score therefore lies within ± 1 standard deviation of the observed score. Accordingly, the larger the SEM, the lower the reliability of the measurement and the less precision there is in the measures taken and scores obtained. The SEM was defined by the equation

\[
SEM = S_x \sqrt{1-ICC}
\]  

(7.2)

where \(S_x\) is the standard deviation of the data [278].

In addition, the 95% confidence intervals (CI) were calculated for all dependent variables to demonstrate how closely the measurements agree on different occasions. F-tests were further applied to investigate levels of significance between groups and individual recordings.

### 7.1.3. Result

Ten healthy individuals (7 women, 3 men) volunteered to participate in this reliability study. Their average age, weight and height were respectively 33.3±4.3, 65.8±9.4 and 170.5±5.2 (Table 7.1.1).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>All subjects (n=10)</th>
<th>Women (n=7)</th>
<th>Men (n=3)</th>
</tr>
</thead>
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<tr>
<td>Age (years)</td>
<td>33.3±4.3</td>
<td>33.6±5.0</td>
<td>32.7±2.3</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>170.5±5.2</td>
<td>168.6±5.1</td>
<td>175.0±1.0</td>
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<tr>
<td>Weight (kg)</td>
<td>65.8±9.4</td>
<td>60.9±5.6</td>
<td>77.3±4.0</td>
</tr>
<tr>
<td>BMI</td>
<td>22.5±2.5</td>
<td>21.3±2.0</td>
<td>21.9±4.8</td>
</tr>
</tbody>
</table>

Table 7.1.1: Participant characteristics

Values are mean ± SD
There were no significant differences between the participant’s demographics as a whole or between genders (Table 7.1.1). Descriptive summaries of the COP-based measures are presented in Table 7.1.2. F-tests demonstrated no significant difference ($p>0.05$) between average scores for any parameter across the trial sequences.

Table 7.1.2: Means, F-test results and p-value for the different trial durations

<table>
<thead>
<tr>
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<th>p-value</th>
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<td>mean ±SD</td>
<td>mean ±SD</td>
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<tr>
<td>mVel ML</td>
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<td>12.3±3.0</td>
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<td>11.6±3.5</td>
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<td>8.7±2.2</td>
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</tr>
<tr>
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<td>38.2±15.6</td>
<td>37.4±13.6</td>
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<td>-1.0±4.9</td>
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<td>0.83</td>
</tr>
<tr>
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<td>-142.3±42.2</td>
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<td>-144.1±43.7</td>
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<td>0.67</td>
</tr>
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</table>

AP: antero-posterior, mVel: mean velocity, ML: medio-lateral, SEM: standard error of measurement, Vel moment: velocity moment
The ICC$_{2,k}$, 95% CI and SEM values are provided in Table 7.1.3. In general, the reliability values increased with both trial duration and the number of repetitions in association with narrower 95% CIs and decreasing SEM values. With three trials of 90sec duration conducted, most COP parameters reached excellent reliability (ICC$_{2,k}$$\geq$0.75).

Table 7.3: ICC$_{2,k}$ values, SEM and 95% confidence intervals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>30 seconds duration</th>
<th>60 seconds duration</th>
<th>90 seconds duration</th>
</tr>
</thead>
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<td></td>
<td>ICC</td>
<td>95% CI</td>
<td>SEM</td>
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<td>.58-97</td>
<td>.96</td>
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<td>mVel AP</td>
<td>.856</td>
<td>.52-96</td>
<td>.83</td>
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<td>Vel mom</td>
<td>.899</td>
<td>.65-97</td>
<td>4.32</td>
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<td>.808</td>
<td>.40-90</td>
<td>1.88</td>
</tr>
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<td>.780</td>
<td>.34-94</td>
<td>19.04</td>
</tr>
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<td>.839</td>
<td>.48-96</td>
<td>1.40</td>
</tr>
<tr>
<td>Dist ML</td>
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<td>.67-98</td>
<td>0.83</td>
</tr>
<tr>
<td>Dist AP</td>
<td>.990</td>
<td>.96-99</td>
<td>0.64</td>
</tr>
</tbody>
</table>

AP: antero-posterior, dist: distance, mVel: mean velocity, ML: medio-lateral, mValue: mean value, SEM: standard error of measurement, Vel mom: velocity moment
The following figures show the results for mVel, 90% circle diameter and velocity moment (Figures 7.1.2 to 7.1.5). The reliability results for mVel ML for example varied between ICC\(_{2,k}\) 0.88 (95% CI .59-.97, SEM 0.96) with two trials of 30 second duration combined to ICC\(_{2,k}\) 0.86 (95% CI .70-.96, SEM 0.98) after 5 trials of 90 seconds.

**Figure 7.1.2:** COP mean velocity in antero-posterior and medio-lateral direction

The grey area indicates the defined level of acceptable reliability (ICC\(_{2,k}\) ≥0.75)
**Figure 7.1.3:** COP circle diameter (mm) of 90% path excursion

The grey area indicates the defined level of acceptable reliability (ICC_{2,k} ≥ 0.75)

**Figure 7.1.4:** COP velocity moment (mm²/s)

The grey area indicates the defined level of acceptable reliability (ICC_{2,k} ≥ 0.75)
The grey area indicates the defined level of acceptable reliability (ICC$_{2,k} \geq 0.75$)

#### 7.1.4. Discussion

The magnitude of the ICC is dependent on the variability of the COP data. The heterogeneity of the participants therefore needs to be carefully considered, as high ICC values may mask poor test-retest consistency if there is a large variability between the participants. Conversely, even in the presence of low inter-participant variability, small test-retest variations may cause low ICC values.

Donner and Eliasziw [279] demonstrated that eight subjects and five trials allow for significantly ($p<0.05$) differentiating ICCs between 0.95 and 0.80 with 80% power. We decided to enroll ten participants performing five trials each for the different sampling durations. The occasionally wide 95% CI reflect the small number of participants (Table 7.1.3).
The overall results of this study are in full agreement with our previous literature review [187] where we concluded that 3 repetitions of 90 sec duration will allow an excellent reliability (Chapter 2). It was further reported that once an acceptable level of reliability was reached, longer sampling durations did not lead to a further significant reduction in variability [106]. Our data confirms this as the results of 60 and 90 seconds were quite consistent for all parameters (Table 7.1.3), an indication that lengthening the trial duration beyond 90 seconds is unlikely to significantly reduce variability any further.

As with previous studies [122, 123, 134, 135], mean sway velocity showed to be the most reliable COP parameter across all trials in both AP and ML direction. While only two trials of 30, 60 or 90sec duration had to be averaged to obtain an ICC$_{2,k} \geq 0.75$, conducting three or more trials lead to a further narrowing of the 95% CI and decreasing SEM.

For many 30sec trial series, the ICC$_{2,k}$ values decrease across the trials which indicate a high variability of the data for this particular duration. In contrast, results of 60 and 90sec show either a relative plateau or increasing reliability values which indicates more consistent readings (Figure 7.1.2 to Figure 7.1.5).

An interesting secondary result was that while mVel AP remained fairly constant regardless of the sampling duration, mVel ML showed to be affected by it (Table 7.1.2). The average sway velocity across 5 trials in ML direction changed from 12mm/s at 30sec to 10.8 mm/s at 90sec duration, which corresponds to a decrease of around 10%. In contrast, the 90% circle diameter increased from 10.7mm (30sec) to 12.1mm at 90sec, an increase of around 12%. This indicates that during the first phase of the recording there is some increased instability, probably associated with the unusual postural task which the participants were progressively able to compensate for with longer sampling durations. Such an adaptation period would be expected if the body is quite suddenly required to "stand as still as possible". This appears to
lead to lower sway velocities while the sway area increases, probably in association with the prolonged deprivation of visual references.

This also indicates that the initial 5 sec that were not recorded is an insufficient time span to allow for this compensation to happen. However, it may still remove some of the initial unrest that may otherwise affect the results even more. As the experimental protocol will consist of three trials of 90 sec duration, further prolonging the allocated time for initial adaptation may exceed the physical limits of pain patients. For future studies, it may be recommended to standardize the initial adaptation period allowed before recordings.

While age per se does not necessarily affect the reliability of results [148], fatigue with prolonged trial duration may be an issue in measurement variability at this point. In Chapter 8 such effects of fatigue and learning effects on COP measurers will be investigated and discussed in detail.

The use of three to five 90 sec recordings may be of concern when working with symptomatic patients. Therefore, we only included asymptomatic participants in order not to exceed their tolerance and potentially affect the reliability of the sway data by (involuntary) pain avoidance movements, particularly with later recordings. The same accounts for individuals older than 50 years where age related changes may affect their balance performance. The feasibility of the experimental setup will be investigated in Chapter 7.2.

7.1.4.1. Selection of parameters for future studies

While the COP parameters "mValue AP/ML" show good reliability based on this study it has not been reported in other studies and given the lack of information from the manufacturer, it
will not be used in this thesis. Although sufficient information about the parameter "distance ML" is available, it will also be excluded from this thesis. As all trials are conducted in narrow stance, the deviation of the COP in lateral direction from the mid-point will be minimal and, as shown in the sample size calculations, no significant difference between healthy controls and symptomatic individuals is expected (Chapter 7.3). The parameter distance AP will be applied only in the reliability pilot study to allow inter-study comparison (Chapter 8).

The difficulty with the validity of the parameter "distance AP" is associated with the fact that the distance between COP and the mid-point of the forceplate not only depends on a defined heel position, but the size of the individual's feet as well. Measuring this was not incorporated in the methodology. However, it may be assumed that similar groups will also have similar distribution in sizes of feet, thereby allowing data analysis. All other parameters included in this reliability study will be used for analysis in the following experiments.

7.1.5. Conclusions

We were able to demonstrate that averaging 3 repetitions of 90 sec duration provide excellent intra-session reliability for all but one of the included COP parameters. Compared to previous studies [96, 97, 101], our experimental setup proved to allow superior reliability values.

7.1.6. Limitations

One of the limitations of this study is the reasonably young age of the participants (33.3±4.3 years). Secondly, their healthy status potentially limits the generalization of results to symptomatic pain sufferers or patients with functional impairments.
CHAPTER 7

7.2. Feasibility pilot study

7.2.1. Background

Before commencing with the pilot and prospective trials of this thesis, the feasibility of the experimental setup identified in Chapter 2 needed to be established to show that symptomatic individuals are able to meet the physical demands of the measurement procedures and feel safe and fairly comfortable at the same time.

7.2.2. Materials and methods

7.2.2.1. Participants

Assuming that the experiment will pose no difficulty for healthy individuals, we aimed at enrolling 20 symptomatic participants. All new patients entering the clinic were asked on the phone whether they would like to take part in the pilot study. In case of interest, they were asked to contact the clinic for further details. After oral and printed information had been given, the subjects consented to participate in this study, which was approved by the Murdoch University Human Research Ethics Committee (Approval 2010/066). The participants of this study were enrolled in the pilot study for sample size calculations in parallel (Chapter 7.3).

Inclusion criteria for the symptomatic participants were very wide and included the presence of pain ≥2 on the NRS-11 scale in any region on the day of the postural sway recordings. There were no restrictions on age or gender. Participants were excluded if they were unable to perform the postural sway recording either due to pain or other reasons.
As the study is simply concerned with the feasibility of the experimental setup, we did assess for previous injury to the neck or lower extremities, balance problems or the usage of medication associated with pain suppression or altered sensory perception but did not exclude any participant based on these findings.

7.2.2.2. Procedures

The experimental setup was following the best practice setup with regards to the reliability of COP data presented (Chapter 2). Accordingly, trials were conducted with eyes closed as the data obtained shows higher reliability than with eyes open. We further considered that the loss of visual input will prove an additional challenge to the balance system.

The choice of COP parameters is of no concern for the purpose of this study, the respective results are included in and presented as part of other associated studies.

The participants were asked to remove their shoes and stand upright on the forceplate with their eyes closed, the head erect and their arms hanging loosely by their sides. The foot position was narrow stance with toes and heels touching. For the duration of the recording, the participants were further instructed to "stand as still as possible" [276].

Three successive trials of 90 seconds duration each were conducted with a preceding 5 sec adaption period that was not recorded. Rest periods of 60 sec were provided between each trial during which the participants were allowed to sit down while maintaining their original foot position. All participants were asked afterwards whether pain or discomfort may have influenced their balance performance.
All tests were conducted in a quiet room with normal temperature and lighting. The forceplate was calibrated prior to the recordings and further underwent an automatic calibration check before each trial.

To assess for the participants were asked the following five basic questions after the recording:

1) Did you find the sequence physically demanding? (yes/no)
2) Did you feel that the pain/discomfort you are experiencing has altered your ability to perform the test? (yes/no)
3) Did you feel safe during the measurements? (yes/no)
4) Were the instructions easy to follow? (yes/no)
5) Do you have any suggestions to make the procedures more comfortable?

If Question 4 was answered with "no", the patient was asked which aspect(s) of the instructions he/she was referring to.

7.2.3. Statistical analysis

Simple descriptive statistics were used for data analysis. Means and SD were calculated for all dependent variables. All data were exported to PASW® Statistics 18 (SPSS Inc, 2009) for statistical analysis.
7.2.4. Results

7.2.4.1. Participants

Twenty individuals suffering various biomechanical complaints volunteered to participate in this study.

We enrolled sixteen male and four female participants with an average age of 38.8±13.6yrs, a height of 175.5±7.1cm and a weight of 77.7±11.3kg. The majority of participants suffered from pain in the lumbo-pelvic area (19/20, 95%). The NRS-11 scores ranged from 2-8 with an average pain intensity of 5.3±2.0. The reported disability as assessed by DRI ranged from 0-867/1200 with an average of 311.0±267.0.

Table 7.2.1: Participant characteristics

<table>
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<th>Participant No.</th>
<th>Age (m/f)</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>Painful area</th>
<th>NRS-11 score</th>
<th>Disability (DRI) Score out of 1200</th>
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<td>31 m</td>
<td>89</td>
<td>185</td>
<td>lumbo-pelvic</td>
<td>7</td>
<td>250</td>
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<tr>
<td>PS 003</td>
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<td>421</td>
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<td>88</td>
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<td>255</td>
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<td>179</td>
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<td>lumbo-pelvic</td>
<td>5</td>
<td>773</td>
</tr>
<tr>
<td>PS 019</td>
<td>20 m</td>
<td>80</td>
<td>186</td>
<td>lumbo-pelvic</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>PS 020</td>
<td>54 m</td>
<td>80</td>
<td>178</td>
<td>lumbo-pelvic</td>
<td>2</td>
<td>190</td>
</tr>
<tr>
<td>PS 021</td>
<td>51 f</td>
<td>60</td>
<td>176</td>
<td>lumbo-pelvic</td>
<td>5</td>
<td>176</td>
</tr>
</tbody>
</table>

f: female, m: male
7.2.4.2. Responses

All participants felt safe during the measurements. One participant reported that she found the task physically difficult and felt that her pain may have affected her balance performance (1/20, 5%). Two other individuals were unclear about aspects of the instructions given during the tasks 2/20, 10%). The following table shows the individual responses of the participants (Table 7.2.2).

Table 7.2.2: Participant's responses

<table>
<thead>
<tr>
<th>Participant No.</th>
<th>Question 1</th>
<th>Question 2</th>
<th>Question 3</th>
<th>Question 4</th>
<th>Referring to</th>
<th>Question 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS 002</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 003</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>foot position</td>
<td>-</td>
</tr>
<tr>
<td>PS 004</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 005</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 006</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 007</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 008</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 009</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 010</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 011</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 012</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 013</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 014</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 015</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 016</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 017</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>Shorter sampling duration</td>
<td>-</td>
</tr>
<tr>
<td>PS 018</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>arm position</td>
<td>-</td>
</tr>
<tr>
<td>PS 019</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 020</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PS 021</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The grey shaded boxes indicate deviating/undesirable responses.

7.2.5. Discussion

Most importantly the participants felt safe during the measurements and generally did not consider the postural tasks physically demanding. Although the vast majority was suffering
from non-specific low back pain we believe that this does not prohibit generalization to patients with pain in other regions.

The patient reporting a high physical demand (PS017) presented with severe pain (NRS-11 score of 8) and fairly high disability rating (695/1200) and discomfort during prolonged standing is to be expected in such a case. For this purpose, every patient is specifically informed about the possibility to abort the measurement at any time should the postural task become too difficult or painful to complete. As a total of 14 patients presented with an NRS score of ≥5 and no other concerns were voiced, a reduction in sampling duration or the number of recordings that may adversely influence the reliability of the results is unnecessary.

The two negative responses with regards to the instructions given concerned minor details such as whether the "toes and ankles had to touch" or not and whether the participant was allowed to "swing the arms" to maintain balance. The respective points were noted and the protocol for instructions updated accordingly.

7.2.6. Conclusions

The broad age range (22-66 yrs) in association with the wide variety of pain intensity (NRS 2-8) and disability (0-867/1200) suggests that the experimental setup is perceived as safe and well suited for enrolling symptomatic individuals fitting the respective study criteria.
CHAPTER 7

7.3. Sample size calculations

7.3.1. Background

The sample size calculations were based on COP measures from a preliminary set of 20 non-specific pain sufferers for each painful region. The results were correlated to those of 60 healthy controls that were matched regarding age, weight, height and BMI. Their demographics of the asymptomatic participants are shown in Table 7.3.1.

<table>
<thead>
<tr>
<th>Healthy controls (n=60)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>38.3±9.1</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176.8±6.5</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>76.6±9.2</td>
</tr>
<tr>
<td>BMI</td>
<td>24.8±3.2</td>
</tr>
</tbody>
</table>

Values are mean ± SD

Sample size calculations were conducted for all three designated symptomatic areas. For this purpose, the standardized differences were calculated (7.3) and applied to the Altman Nomogram [280].

\[
\text{Standardized difference} = \frac{\text{Target difference}}{\text{Standard deviation}} \quad (7.3)
\]

The Altman nomogram links the power of a study to the sample size. The right y-axis represents the chosen power, the left one the calculated standardized difference. In addition, independent sample T-tests were applied to calculate \( p \)-values.
7.3.2. Neck (Region 1)

The characteristics of those patients suffering from NSNP are shown in Table 7.3.2.

**Table 7.3.2:** Demographic and functional characteristics of NSNP patients

<table>
<thead>
<tr>
<th>NSNP (n=20)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>39.1±6.9</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.0±7.6</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>79.7±11.4</td>
</tr>
<tr>
<td>BMI</td>
<td>24.7±2.7</td>
</tr>
<tr>
<td>NRS-11 (0-10)</td>
<td>4.2±1.6</td>
</tr>
<tr>
<td>Previous pain duration (weeks)</td>
<td>14.5±19.4</td>
</tr>
</tbody>
</table>

Values are mean ± SD

On the left, the calculated sample sizes for 90% power are shown for all included parameters.

**Figure 7.3.1:** Altman Nomogram showing sample size required for NSNP sufferers

The numbers to the left refer to the respective COP parameter as shown in Table 7.3.4
Table 7.3.4. shows the results of healthy controls and symptomatic participants, the level of significance of the difference and the resulting required sample size.

Table 7.3.4: Results for painful Region 1 (neck)

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>Results</th>
<th>p-value</th>
<th>Required sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symptomatic (n=20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mVel ML (mm/s)</td>
<td>15.9±5.8</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>12.6±5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13.7±5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Controls (n=60)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mVel AP (mm/s)</td>
<td>13.6±5.7</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>13.4±5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13.5±5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90% circle diameter (mm)</td>
<td>13.8±3.0</td>
<td>≤ 0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13.5±3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13.2±3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>vircular diameter (mm)</td>
<td></td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>11.6±2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.6±3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.9±2.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AP: antero-posterior, mVel: mean velocity, ML: medio-lateral

Values are mean ± SD

* as extracted from Altman Nomogram

These results indicate that about 50 participants need to be enrolled for the velocity based parameters (mVel AP/ML, velocity moment) and around 85 for 90% circle diameter as an expression of sway area.

7.3.3. Mid-back (Region 2)

The characteristics of patients with non-specific mid back pain (NSMBP) are shown in Table 7.3.5.
Table 7.3.5: Demographic and functional characteristics

<table>
<thead>
<tr>
<th></th>
<th>Mid-back pain (n=20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>37.7±11.3</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176.8±8.2</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>78.3±12.0</td>
</tr>
<tr>
<td>BMI</td>
<td>24.8±2.1</td>
</tr>
<tr>
<td>NRS-11 (0-10)</td>
<td>3.8±1.8</td>
</tr>
<tr>
<td>Previous pain duration (weeks)</td>
<td>12.3±17.5</td>
</tr>
</tbody>
</table>

Values are mean ± SD

Figure 7.3.2: Altman Nomogram showing sample size required for patients with mid-back pain

The numbers to the left refer to the respective COP parameter as shown in Table 7.3.6

As for mid-back pain patients, Table 7.3.6. shows the COP measures of healthy controls and symptomatic individuals, the level of significance of the difference and the resulting required sample sizes.
Table 7.3.6: Results for painful Region 2 (mid back/thoracic spine)

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>Symptomatic (n=20)</th>
<th>Controls (n=60)</th>
<th>p-value</th>
<th>Required sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mVel ML (mm/s)</td>
<td>13.4±4.3</td>
<td>11.9±2.5</td>
<td>0.003</td>
<td>200</td>
</tr>
<tr>
<td>2 mVel AP (mm/s)</td>
<td>11.7±4.3</td>
<td>9.3±2.3</td>
<td>≤ 0.0001</td>
<td>130</td>
</tr>
<tr>
<td>3 90% circle diameter (mm)</td>
<td>12.4±2.9</td>
<td>11.6±2.5</td>
<td>0.007</td>
<td>330</td>
</tr>
</tbody>
</table>

AP: antero-posterior, mVel: mean velocity, ML: medio-lateral
Values are mean ± SD

* as extracted from Altman Nomogram

In contrast to neck pain patients, the calculations for Region 2 indicate much larger required sample sizes of 130 (mVel AP) to about 330 (90% circle diameter) participants.

7.3.4. Low back and pelvis (Region 3)

In Table 7.3.7., the patient characteristics of NSLBP sufferers are shown.

Table 7.3.7: Demographic and functional characteristics

<table>
<thead>
<tr>
<th>NSLBP (n=20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>Height (cm)</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
<tr>
<td>BMI</td>
</tr>
<tr>
<td>NRS-11 (0-10)</td>
</tr>
<tr>
<td>Previous pain duration (weeks)</td>
</tr>
</tbody>
</table>

Values are mean ± SD
On the left, the calculated sample sizes for 90% power are shown for all included parameters. The right diagram compares the results of the current prospective trial to values from Salavati et al. [185] which also originated from the COP parameter mean velocity (mVel) (Figure 7.3.3). This parameter is of primary importance for the experiment as it has been shown to be the most reliable and discriminative parameter [187]. The results suggest that our experimental setup based on the reliability literature review (Chapter 2) is more sensitive.

Figure 7.3.3: Altman Nomogram showing sample size required for NSLBP sufferers

As before, the results of healthy controls and symptomatic participants, the level of significance of the difference and the resulting required sample size are shown in the following Table (Table 7.3.8).
Table 7.3.8 Results for painful Region 3 (lumbar spine/pelvis)

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>Results</th>
<th>p-value</th>
<th>Required sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symptomatic (n=20)</td>
<td>Controls (n=60)</td>
<td></td>
</tr>
<tr>
<td>1 mVel ML (mm/s)</td>
<td>16.0±3.4</td>
<td>11.9±2.5</td>
<td>≤ 0.0001</td>
</tr>
<tr>
<td></td>
<td>14.7±3.7</td>
<td>11.3±2.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14.9±3.8</td>
<td>11.5±2.7</td>
<td></td>
</tr>
<tr>
<td>2 mVel AP (mm/s)</td>
<td>12.3±3.2</td>
<td>9.3±2.3</td>
<td>≤ 0.0001</td>
</tr>
<tr>
<td></td>
<td>12.7±3.7</td>
<td>9.0±2.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.6±4.4</td>
<td>9.3±2.4</td>
<td></td>
</tr>
<tr>
<td>3 90% circle diameter (mm)</td>
<td>13.5±2.5</td>
<td>11.6±2.5</td>
<td>≤ 0.0001</td>
</tr>
<tr>
<td></td>
<td>13.8±2.3</td>
<td>11.6±3.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13.5±3.3</td>
<td>11.9±2.5</td>
<td></td>
</tr>
</tbody>
</table>

AP: antero-posterior, mVel: mean velocity, ML: medio-lateral
Values are mean ± SD
* as extracted from Altman Nomogram

7.3.5. Conclusion

Although the differences are mostly highly significant (p≤0.01) already with 20 samples, the magnitude of the standard deviations suggest a larger sample size for all parameters. Based on these results, the aim may be to enroll 100-150 participants for both symptomatic and control group to significantly overpower the experiment.
INTER- AND INTRASESSION EFFECTS OF LEARNING AND FATIGUE ON COP MEASURES IN HEALTHY INDIVIDUALS
CHAPTER 8

Inter- and intrasession effects of learning and fatigue on COP measures in healthy individuals

8.1. Background

Some of the inter-subject and inter-session variability observed in COP recordings may be explained by learning effects [109], fatigue [281-284] or boredom which may occur irrespective of the visual condition [282]. Although the studies concerned induced muscle fatigue by exercise, any prolonged standing associated with long sampling durations or repetitive testing may exhibit a similar effect.

When assessing potential intervention effects, the presence of any systematic bias must be detected to allow for necessary statistical adjustments. Systematic bias is a non-random change in the values between two trials whereby the participants perform consistently different in one trial resulting from learning or fatigue effects [285].

In other words, decreased COP excursions may be noted if a learning effect took place [109, 140], which is thought to be an optimization of energy expenditure by progressively reducing body sway over the course of repetitions [140]. In contrast, an increase in body sway with trial repetitions is thought to indicate fatigue [282, 283] or possibly boredom.

The previous literature reviews show that this is the first study to answer the clinical question based on a best evidence experimental setup.
8.2. Materials and methods

8.2.1. Participants

The healthy individuals enrolled in this study were a convenience sample of n=20 taken from previously enrolled participants and snowball sampling from these participants. After both oral and printed information had been given, the subjects consented to participate in this study, which was approved by the Murdoch University Human Research Ethics Committee (Approval No. 2010/066).

For the purpose of this experiment, healthy was defined as the absence of any self-reported neurological or musculoskeletal impairments, pain or disability for a minimum of 6 months prior to the time of evaluation. As postural sway may be influenced by age [12, 105, 148], only participants below 50yrs of age were applicable. Individuals with a history of back pain within the last six months or previous injury to the neck or lower extremities, any known balance problems or the usage of medication associated with pain suppression or altered sensory perception were excluded. The physical screening must also have ruled out any back or extremity complaints or significant biomechanical impairments, such as decreased range of motion, that might influence the COP measurements.

The physical characteristics of those included are presented in Table 8.1.

Table 8.1: Participant characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Intersession group (I) (n=10)</th>
<th>Intraseesion group (II) (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>31.0±3.5</td>
<td>30.4±5.1</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>175.5±7.7</td>
<td>172.8±6.6</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>77.5±7.5</td>
<td>73.3±9.5</td>
</tr>
<tr>
<td>BMI</td>
<td>25.1±1.9</td>
<td>24.1±1.5</td>
</tr>
</tbody>
</table>

Values are mean ± SD
The allocation to either group was based on the participant's availability and preference, no randomization was applied. It could not be ensured that the recordings took place at the same time of day.

8.2.2. Measurement equipment and procedures

The trials were conducted under visual deprivation as the data obtained shows higher reliability compared to measurements with eyes open.

A cluster of four COP parameters was chosen which consisted of mean sway velocity (mVel) in AP and ML direction, 90\% circle diameter and mean COP position in AP direction. Of these, particularly mVel has consistently shown to be both highly reliable [92] and discriminative [216]. The other two parameters are exclusively distributed with the Metitur system and did not widely appear in related literature. For a detailed comprehensive description, see Chapter 6.6.

Prior to the measurements all participants received a physical examination to assess for significant functional impairments or painful areas that may influence the recordings. The participants were then asked to remove their shoes and stand upright on the forceplate with their eyes closed, the head erect and their arms hanging loosely by their sides. The foot position was narrow stance with toes and heels touching. For the duration of the recording, the participants were further instructed to "stand as still as possible" [276].

The participants were divided into two groups with different recording schedules to assess potential inter- and intrasession changes in COP measures across the respective trial series. Group I (n=10) conducted 10 successive trials of 90 seconds duration each. Group II (n=10)
was measured at 3-4 day intervals and completed three successive recordings of 90 sec duration following the procedures described above (Figure 8.1).

Figure 8.1: Structure for assessing learning or fatigue effects during COP measurements

Rest periods of 60 sec were allocated between each trial during which the participants were allowed to sit down while maintaining their original foot position. An initial additional 5 sec period was not recorded to allow the participant to adapt to the postural task. All participants
were asked afterwards whether pain, discomfort or fatigue may have influenced their balance performance.

The tests were conducted in a quiet room with standardized temperature and lighting. The forceplate was calibrated prior to the recordings and further underwent an automatic calibration check before each trial.

8.2.3. Statistical analysis

Means and 95% CIs were calculated for all dependent variables. F-tests were applied to investigate levels of significance between groups and individual recordings. The level of statistical significance was set at $p \leq 0.05$.

All data were exported to PASW® Statistics 18 (SPSS Inc, 2009) for statistical analysis.

8.3. Results

8.3.1. Participant characteristics

Although the average body weight of the participants in the intersession group was slightly higher ($78.1 \pm 6.1$kg compared to $74.7 \pm 5.7$kg), there were no significant differences in participant characteristics between the two groups. No participants had to be excluded based on the physical examination findings. In addition, none reported that fatigue or discomfort may have influenced their balance performance.
8.3.2. Learning and fatigue effects

Table 8.2 and 8.3. show the COP measures obtained during repetitive recordings. There were no significant changes in postural sway measured either intra- or intersession. The respective $p$-values ranged from 0.31 (mean COP position AP) to 0.88 (90% circle diameter) intersession and from 0.27 (mean COP position AP) to 0.75 (mVel ML) intrasession.
Table 8.2: Results for 10 repetitions of 90 sec duration in single session (Group I)

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mVel ML</td>
<td>11.4</td>
<td>11.6</td>
<td>11.8</td>
<td>11.5</td>
<td>11.1</td>
<td>11.3</td>
<td>11.1</td>
<td>11.7</td>
<td>11.2</td>
<td>11.7</td>
<td>0.86</td>
</tr>
<tr>
<td>9.8- (13.1) ± 2.3 (2.1)</td>
<td>± 2.6</td>
<td>± 2.7</td>
<td>± 2.5</td>
<td>± 2.0</td>
<td>± 2.8</td>
<td>± 3.1</td>
<td>± 3.1</td>
<td>± 3.1</td>
<td>± 3.1</td>
<td>± 3.1</td>
<td></td>
</tr>
<tr>
<td>mVel AP</td>
<td>10.1</td>
<td>10.1</td>
<td>10.8</td>
<td>10.3</td>
<td>10.0</td>
<td>9.5</td>
<td>9.6</td>
<td>9.8</td>
<td>9.7</td>
<td>9.7</td>
<td>0.68</td>
</tr>
<tr>
<td>8.7- (11.4) ± 2.2 (2.9)</td>
<td>± 2.3</td>
<td>± 2.3</td>
<td>± 2.1</td>
<td>± 1.4</td>
<td>± 1.8</td>
<td>± 2.1</td>
<td>± 2.1</td>
<td>± 2.1</td>
<td>± 2.1</td>
<td>± 2.1</td>
<td></td>
</tr>
<tr>
<td>90% circle diameter</td>
<td>11.5</td>
<td>11.6</td>
<td>12.4</td>
<td>12.0</td>
<td>12.1</td>
<td>11.8</td>
<td>11.9</td>
<td>12.1</td>
<td>12.1</td>
<td>12.5</td>
<td>0.88</td>
</tr>
<tr>
<td>9.4- (13.9) ± 2.9 (3.2)</td>
<td>± 2.8</td>
<td>± 2.6</td>
<td>± 3.7</td>
<td>± 2.5</td>
<td>± 2.8</td>
<td>± 3.2</td>
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<td>± 3.2</td>
<td>± 3.2</td>
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</tr>
<tr>
<td>Mean</td>
<td>140.8</td>
<td>141.8</td>
<td>142.5</td>
<td>138.4</td>
<td>142.5</td>
<td>144.6</td>
<td>137.4</td>
<td>138.4</td>
<td>131.2</td>
<td>138.9</td>
<td>0.31</td>
</tr>
<tr>
<td>COP position</td>
<td>-157.4 (-159.3)</td>
<td>-154.8</td>
<td>-155.0</td>
<td>-152.2</td>
<td>-153.5</td>
<td>-153.3</td>
<td>-152.6</td>
<td>-161.2</td>
<td>-169.9</td>
<td>-29.3</td>
<td></td>
</tr>
<tr>
<td>AP</td>
<td>-124.2</td>
<td>-124.4</td>
<td>-120.2</td>
<td>-121.9</td>
<td>-125.7</td>
<td>-120.8</td>
<td>-113.1</td>
<td>-116.1</td>
<td>-109.7</td>
<td>-117.9</td>
<td></td>
</tr>
</tbody>
</table>

Values are mean ± SD and (95% CI)
AP: antero-posterior, mVel: mean velocity, ML: medio-lateral
The grey shaded area indicates the number of repetitions (n=3) applied in the prospective study
Overall, the COP measures obtained on three different occasions were more consistent. Also, there were generally lower standard deviations for the parameters 90% circle diameter and velocity moment for this group (Table 8.3).

<p>| Table 8.3: Results for 3 repetitions of 90 sec duration across three sessions (Group II) |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|</p>
<table>
<thead>
<tr>
<th>COP parameter</th>
<th>Repetitions</th>
<th>Repetitions</th>
<th>Repetitions</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Session 1</td>
<td>Session 2</td>
<td>Session 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Recording number</td>
<td>Recording number</td>
<td>Recording number</td>
<td></td>
</tr>
<tr>
<td>mVel ML</td>
<td>11.9 ±2.4 (9.6-13.2)</td>
<td>11.5 ±2.5 (9.7-13.2)</td>
<td>11.5 ±2.6 (9.6-13.3)</td>
<td>0.75</td>
</tr>
<tr>
<td>mVel AP</td>
<td>10.9 ±2.4 (8.1-12.7)</td>
<td>8.8 ±2.0 (7.4-10.8)</td>
<td>8.7 ±2.1 (7.2-10.5)</td>
<td>0.52</td>
</tr>
<tr>
<td>90% circle diameter</td>
<td>11.6 ±3.2 (9.4-13.9)</td>
<td>11.7 ±3.8 (10.3-14.4)</td>
<td>11.7 ±3.3 (10.7-14.6)</td>
<td>0.65</td>
</tr>
<tr>
<td>Mean COP position</td>
<td>-136.7 ±23.6 (-136.7-156.7)</td>
<td>-145.4 ±15.7 (-155.7-137.4)</td>
<td>-142.6 ±15.7 (-159.5-131.2)</td>
<td>0.27</td>
</tr>
<tr>
<td>Mean AP</td>
<td>-139.9 ±23.6 (-139.9-156.4)</td>
<td>-145.4 ±15.7 (-145.4-137.4)</td>
<td>-142.6 ±15.7 (-159.5-131.2)</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Values are mean ± SD and (95% CI)

AP: antero-posterior, mVel: mean velocity, ML: medio-lateral

All participants of the inter-session group attended the required number of recordings with an average interval of 2.7±0.7 days between recordings (data not shown).
8.4. Discussion

No significant learning or fatigue effects could be demonstrated in either group. However, the small sample size may mask the existence of such an effect. It also has to be kept in mind that the results reported here only apply for our specific experimental setup.

To avoid fatigue, previous studies have allowed up to 5min of rest between the trials [126, 286]. When applying the recommended three repetitions of 90sec duration [92], this would bring the overall time investment to about 15min per session. This study shows that 1min breaks are both sufficient and better suited for the time restraints normally associated with a clinical setting.

The fact that the results show some variation between the two groups can firstly be attributed to normal inter-subject variability associated with the low sample size in each group (n=10). Secondly, the higher weight of participants in the intra-session group (73.3±9.5kg compared to 77.5±7.5kg) may play a role [147]. However, the presence of such discrepancy is of no concern for our conclusions.

It is difficult to relate our results to previous research as only few studies directly assessed for potential learning during COP measures and none directly investigated or observed effects of naturally occurring, non-induced (muscle) fatigue during the measuring process.

8.4.1. Inter-session effects

Nordahl et al. [109] found that the maximum learning occurred on a foam surface with the eyes closed and with the shortest interval between test sessions. While they found no learning
effects for any stance in which the eyes were open, they noted high learning potential with loss of visual reference.

Although the participant characteristics were similar, our results do not support these findings and several reasons may explain this. Any variability in COP sway caused by an initial adaptation period at the beginning of each recording may decrease as the individual gets accustomed to the task. Such a learning effect is more likely to equal out with the reasonably long sampling duration and multiple repetitions applied in our study compared to single measures of shorter duration (60sec) as applied by Nordahl et al. [109].

Secondly, the unstable and unusual surface condition may necessitate or facilitate learning effects in contrast to the hard and stable surface used in this study.

Another difference is that our inter-session participants were re-tested after less than 4 days while the minimal interval investigated by them was around eleven days. However, as Nordahl et al. [109] concluded that a maximal learning effect occurred during short intervals, similar changes in COP excursions should have been apparent in our results.

The low variability of results within our intra-session group is quite surprising as one would expect changing postural sway due to the varying times of day and associated different levels of physical activity prior to the recordings. The homogeneous physical characteristics and the young average age may explain these findings.
8.4.2. Intra-session effects

While we are aware that ten consecutive trials are highly impractical in clinical practice we decided on this procedure as any trend towards greater postural sway may indicate an effect of fatigue. Here, no such effect could be demonstrated and no trend towards greater postural sway was found with increasing number of measurements. Again, this may be attributed to the relatively young age, good physical status and the high motivation of the participants as well as the arrangement of appropriate resting periods between the trials.

Tarantola et al. conducted two blocks of 10 consecutive recordings of 51sec duration with eyes open (m=20) and closed (n=20) in narrow and normal stance each [140]. They noted a progressive decrease in postural sway under eyes closed condition in narrow stance with a significant reduction in COP sway area and path length of up to 50%. They also described a significant, progressive shift in COP mean position in AP direction.

It was hypothesized that in the adaptive process, the central nervous system may take better advantage of the afferent input from the proprioceptors under visual deprivation. They further interpret their findings as evidence that, as with other types of motor behavior, repetition of the task leads to learning, and in turn to optimizing motor performance. In this context, optimization would require a reduction of body sway, since greater sway requires larger metabolic expenditure for adaptive muscle activation [140]. No further evidence was presented to support their conclusions with regards to the neural processes.

Again, our results are not in agreement and it is difficult to conclude why. Despite the lower sampling frequency (10Hz compared to 100Hz), the lower sampling duration (51sec compared to 90sec) and the rather heterogeneous group (age range 18–49yrs compared to 31.0±3.5yrs), none of these factors alone is likely to account for the different results. As the relevant data
was not provided, it is not possible to assess whether any variations in their respective body weight or height may have influenced postural sway.

Furthermore, any significant reduction ($p \leq 0.05$) in postural sway occurred after the second (COP mean position), third (path length) or the last block (sway area), indicating 10 to 20 repetitions over 20 to 40 min respectively. Our 10 repetitions were conducted within just about 25 min. However, considering the magnitude of the $p$-values associated with our results, it appears unlikely that a similar effect would have been observed even after more time. Secondly, even if such an effect existed, the overall duration and number of repetitions necessary to reach significance appears far beyond the scope of clinical interest.

8.4.3. Clinical significance

Although care was taken to select representative patient samples, the COP data from healthy individuals may mask the presence of postural adaptations due to pain avoidance potentially exhibited by symptomatic patients. Due to ethical considerations we deemed it inappropriate to enroll (acute) pain sufferers for a trial duration of more than a week without providing relief, a reason that may not fully apply to patients with chronic pain.

Secondly, any intra-session variability in results may be attributable to variations in subjective pain perception as there is a linear relationship between postural sway and pain intensity [217]. This renders any interpretation of inter-session results of pain sufferers difficult.

The results of this study nevertheless suggest that any reduction in COP excursions observed in repetitive testing, particularly inter-session, may be associated with proprioceptive training [234], a reduction in pain perception due to natural course or an intervention or rehabilitation
process rather than to learning. This may strengthen the clinical application of routine individual COP measures.

8.5. Conclusions

The results did not demonstrate any significant intra- and intersession learning or fatigue effects on postural sway for our specific experimental setup. While the young age of the participants prohibits any generalization of the results to an elderly population, the magnitude of the $p$-values suggest that such effects are unlikely to exhibit significance at any age or clinically applicable sample size. No conclusions can be drawn whether the results observed here also accounts for symptomatic patients.

Future research should consider enrolling an additional group of chronic pain sufferers to assess for potential alterations in postural sway due to pain avoidance in addition to effects of learning and fatigue in single session. When comparing intra-session measures, the problem with varying pain intensities has to be considered and perceived pain levels should be assessed prior to the recordings.
IS THERE A RELATIONSHIP BETWEEN PAIN INTENSITY AND POSTURAL SWAY IN PATIENTS WITH NON-SPECIFIC LOW BACK PAIN?


EAC Jean Robert Research Award, Best Experimental Research Paper, European Chiropractors’ Union, ECU Convention, 02-04 June 2011, Zurich, Switzerland.
CHAPTER 9

Is there a relationship between pain intensity and postural sway in patients with non-specific low back pain?

9.1. Background

As previously outlined in Chapter 5, it still remains to be determined whether the intensity of NSLBP is correlated with the magnitude of postural sway. This is worthy of investigation as it may show clinical significance for the application of COP measures.

In order to assess a possible correlation between pain intensity and postural sway various factors need to be considered as possible confounders. Our aim was to investigate whether the perceived pain level has functional consequences in terms of COP excursions and whether factors such as age [12, 105, 148], gender, weight [147], height [146] or previous pain duration also exhibit a significant effect on postural sway.

This is the first study to investigate this clinical question with a best practice experimental setup and also the first to comprehensively assess the relationship between pain and COP excursions over a wide spectrum of pain scores.

9.2. Materials and methods

The materials, methods and definitions described here remain identical for all following experiments and will only be mentioned again if the focus of the respective study made deviations necessary.
9.2.1. Participants

We aimed at enrolling around 80 participants for both symptomatic and control group. Previous sample size calculations for a group of controls and symptomatic patients with an NRS-11 score of 5.0±2.1 using an Altman Nomogram [280] suggested recruitment of around 50 symptomatic and healthy participants each. We decided to exceed this number in order to compensate for potential dropouts.

All new patients entering the clinic were asked on the phone whether they would like to take part in this study. The healthy controls were friends and partners of already enrolled patients and were initially approached by them regarding the possibility of participation. If they displayed interest they were asked to contact the clinic for further details. After oral and printed information had been given, the subjects consented to participate in this study, which was approved by the Murdoch University Human Research Ethics Committee (Approval 2010/173).

The cut-off age for both controls and symptomatic individuals was 50 years as after that age related impairments to postural stability could not be excluded [12, 105, 148].

Inclusion criteria for the symptomatic participants were NSLBP of any duration and the presence of pain ≥2 on the NRS-11 scale on the day of the postural sway recordings. Participants were excluded if the pain went below the gluteal fold, there were positive nerve root findings, serious spinal deformities or previous significant injuries such as traumatic damage to the spine or spinal surgery. No pain medication was allowed within 24hrs prior to the recordings. Participants were also excluded if they were unable to perform the postural sway recording either due to pain or other reasons. We aimed at enrolling around 10 patients for all 10 pain intensity groups (NRS 1-10).
For the purpose of this study, healthy was defined as the absence of any self-reported neurological or musculoskeletal impairments, pain or disability for a minimum of 6 months prior to the time of evaluation. Specifically, individuals with a history of low back pain within 6 months or previous injury to the neck or lower extremities, any known balance problems or the usage of medication associated with pain suppression or altered sensory perception were excluded. The physical examination of the control group must also have ruled out any back or extremity complaints or significant biomechanical impairments that might influence the measurements.

### 9.2.2. Procedures

Prior to the COP measurements, a physical examination was conducted on all participants by two experienced and trained chiropractors (TB and AS) who were otherwise not involved in the study. This procedure aimed to assess whether the volunteers fit the criteria for their respective group and met the physical demands of the study. The patients were further asked to describe their pain intensity at the time of recording by means of an NRS-11, a rating scale ranging from 0 (no pain) to 10 (worst possible pain) [244].

After obtaining consent, patients were informed that they may be eligible to participate and were handed the health questionnaire. Based on their pain ratings, they were either invited for the COP measurements or excluded if they were not among those individuals required fill their corresponding NRS score group. The patients were blinded to what pain score was needed.

The experimental setup was based on an earlier literature review where a best practice setup with regards to the reliability of COP data was published [92] (Chapter 2). Accordingly, trials were conducted with eyes closed as the data obtained shows higher reliability than with eyes
open. We further considered that the loss of visual input will prove an additional challenge to the balance system. Deficits in proprioception may therefore be more easily detected and the discriminative value of the measurement between healthy controls and symptomatic patients enhanced.

Mean velocity (mVel) was chosen as the main COP parameter as this has consistently shown to be both reliable [92] and discriminative for NSLBP [216]. In addition, 90% circle diameter was included as an area based parameter to offer a broader spectrum of analysis.

The participants were asked to remove their shoes and stand upright on the forceplate with their eyes closed, the head erect and their arms hanging loosely by their sides. The foot position was narrow stance with toes and heels touching. For the duration of the recording, the participants were further instructed to "stand as still as possible" [276].

Three successive trials of 90 seconds duration each were conducted with a preceding 5 sec adaption period that was not recorded. Rest periods of 60 sec were provided between each trial during which the participants were allowed to sit down while maintaining their original foot position. All participants were asked afterwards whether pain or discomfort may have influenced their balance performance.

All tests were conducted in a quiet room with normal temperature and lighting. The forceplate was calibrated prior to the recordings and further underwent an automatic calibration check before each trial.
9.3. Data analysis

To test if postural sway may be influenced by age [12, 105, 148], the participants were subdivided into two age ranges and subsequently compared to see if they statistically differ from each other. Group one consisted of those between 20-35yrs, the second of those 36-50yrs of age. If, however, our study showed no significant differences, the age groups were to be combined for further analysis to reduce the risk of a type-II error.

9.3.1. Reliability

To test the reliability of the COP measures for this experimental setup with pain sufferers, the two-way mixed-effect intra-class correlation coefficient (ICC$_{2,k}$) as described by Shrout et al. [138] was computed. In addition, the SEM and 95% confidence intervals (CI) were calculated. For the purpose of this study it was interpreted using the following criteria: 0.0-0.39 poor, 0.40-0.59 fair, 0.60-0.74 good and 0.75-1.00 excellent [277].

9.3.2. Pain intensity and COP excursions

We also tested the assumptions of homogeneity of variance (Levene statistic) and normality, where Shapiro-Wilk test was conducted for all independent variables and the dependent variables separately per pain level group. The COP data was further analyzed using the Games-Howell test. Means, SDs and 95% CIs were calculated for all variables.

Stepwise univariate regression analysis was conducted to assess for the possible effect of each of the following variables: age, gender, weight, height, pain intensity and previous pain
duration on COP mVel and 90% circle diameter. This was followed by a multivariate regression analysis including the independent variables that showed a significant effect during univariate analysis.

To investigate the appropriate form of regression analysis, the SPSS Curve Estimation function was applied to scatter plots for variables stated above (independent variables) and the COP parameters (dependent variables). In addition, the collinearity diagnostics were applied. The level of statistical significance was set at $p \leq 0.05$.

9.3.3. Main sway direction

Based on the COP parameter "direction of main axis", which is a coefficient of the angle in degrees, the 360° circle was subdivided into two sections. Section 1 consisted of the 90° angles facing front and backwards (AP), Section 2 covered the angles left and right (ML). A detailed description of these angles can be found in Chapter 6.5.3. The sway direction results were analyzed individually for each of the three consecutive measurements and added up to calculate overall percentages.

All data were exported to PASW® Statistics 18 (SPSS Inc, 2009) for statistical analysis.

9.4. Results

9.4.1. Participants

Eighty-two individuals suffering from NSLBP initially volunteered to participate in this study. We were not able to enroll our target number of at least 10 patients for NRS scores 1 (n=2), 9
(n=2) and 10 (n=0) and therefore only included NRS scores 2-8 with 11 patients each. Four symptomatic participants were excluded as they exhibited severe pain (n=4) or an antalgic posture (n=1) when standing and were unable to complete the tests. This left a total of 77 NSLBP sufferers (37 females, 45%) to which a matching number of healthy controls was enrolled (Table 9.1).

**Figure 9.1: Structure of experimental procedures**

All participants were able to complete the trials without difficulty. The characteristics of the participants are shown in Table 9.1.
Table 9.1: Demographic and functional characteristics

<table>
<thead>
<tr>
<th></th>
<th>NSLBP Age 20-35 (n=32)</th>
<th>Healthy controls Age 20-35 (n=36)</th>
<th>Statistical difference</th>
<th>NSLBP Age 36-50 (n=45)</th>
<th>Healthy controls Age 36-50 (n=41)</th>
<th>Statistical difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>28.9±4.7</td>
<td>29.8±4.4</td>
<td>0.89</td>
<td>44.1±4.3</td>
<td>43.5±5.5</td>
<td>0.67</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.0±6.6</td>
<td>177.2±7.4</td>
<td>0.36</td>
<td>179.2±7.6</td>
<td>176.9±6.9</td>
<td>0.37</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>77.6±9.5</td>
<td>77.3±11.7</td>
<td>0.47</td>
<td>80.8±12.8</td>
<td>76.9±8.8</td>
<td>0.71</td>
</tr>
<tr>
<td>BMI</td>
<td>24.3±2.7</td>
<td>24.9±3.9</td>
<td>0.60</td>
<td>25.1±2.9</td>
<td>24.5±1.9</td>
<td>0.11</td>
</tr>
<tr>
<td>NRS-11 (0-10)</td>
<td>4.9±1.9</td>
<td>N/A</td>
<td>N/A</td>
<td>5.1±2.1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Previous pain duration</td>
<td>19.9±33.6</td>
<td>N/A</td>
<td>N/A</td>
<td>18.7±30.5</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Values are mean ± SD. * compared to control groups

NSLBP: non-specific low back pain

9.4.2. Reliability

With three recordings being averaged from both healthy controls and symptomatic participants, the included COP parameters reached good reliability throughout (Table 9.2).

Table 9.2: Reliability of COP measures

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>NSLBP (n=77)</th>
<th>Healthy controls (n=77)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC2,k</td>
<td>95%CI</td>
</tr>
<tr>
<td>mVel ML</td>
<td>0.85</td>
<td>0.79-0.99</td>
</tr>
<tr>
<td>mVel AP</td>
<td>0.83</td>
<td>0.76-0.88</td>
</tr>
<tr>
<td>90% circle diameter</td>
<td>0.71</td>
<td>0.61-0.79</td>
</tr>
</tbody>
</table>

AP: antero-posterior, mVel: mean velocity, ML: medio-lateral, NSLBP: non-specific low back pain

9.4.3. Learning effect

There was no apparent learning effect as there were no significant differences between the postural sway measurements across the trial series for both symptomatic individuals and healthy controls.
9.4.4. Age groups

Both age groups had a similar number of healthy participants with n=36 for 18-35yrs and n=41 for 36-50yrs. As there was no statistically significant difference in COP measures between the two age groups (Table 9.3), the data was combined and analyzed for the control group as a whole.

Table 9.3: Comparison of COP data between the age groups

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>Healthy controls</th>
<th></th>
<th>Healthy controls</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20-35 yrs (n=36)</td>
<td></td>
<td>36-50 yrs (n=41)</td>
<td></td>
</tr>
<tr>
<td>mVel ML (mm/s)</td>
<td>11.8±2.5</td>
<td>12.0±2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mVel AP (mm/s)</td>
<td>9.1±2.7</td>
<td>9.5±2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90% circle diameter (mm)</td>
<td>11.6±2.8</td>
<td>12.0±2.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are mean ± SD

AP: antero-posterior, mVel: mean velocity, ML: medio-lateral

9.4.5. Differences in postural sway between pain suffersers and controls

Generally, patients with NSLBP exhibited a greater postural instability than healthy controls signified by an increased mean sway velocity and sway area. The following picture typically illustrates the significantly increased COP excursions exhibited by a 36 years old patient with an NRS-11 score of 7 compared to an age-matched healthy control (Figure 9.2).
9.4.6. Relationship between pain intensity and postural sway

As a general trend, higher sway velocities (mVel) in both antero-posterior (AP) and medio-lateral (ML) direction can be observed with higher pain levels (Table 9.4).

Table 9.4: Pain intensity and postural sway at baseline

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>2 (n=11)</th>
<th>3 (n=11)</th>
<th>4 (n=11)</th>
<th>5 (n=11)</th>
<th>6 (n=11)</th>
<th>7 (n=11)</th>
<th>8 (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mVel ML (mm/s)</td>
<td>11.5±2.2 (10.7-12.3)</td>
<td>12.4±2.8 (11.4-13.4)</td>
<td>13.1±3.1 (12.0-14.2)</td>
<td>13.9±3.7 (12.6-15.2)</td>
<td>15.6±2.6 (14.7-16.6)</td>
<td>18.6±2.4 (17.7-19.4)</td>
<td>21.2±3.5 (20.0-22.5)</td>
</tr>
<tr>
<td>mVel AP (mm/s)</td>
<td>9.8±2.2 (9.0-10.8)</td>
<td>11.1±3.0 (10.1-12.2)</td>
<td>11.2±3.2 (10.1-12.4)</td>
<td>12.9±4.3 (11.3-14.4)</td>
<td>13.0±2.1 (12.2-13.7)</td>
<td>15.8±3.1 (14.7-16.9)</td>
<td>18.4±4.5 (16.8-20.0)</td>
</tr>
<tr>
<td>90% circle diameter (mm)</td>
<td>12.3±2.2 (11.5-13.1)</td>
<td>12.4±2.6 (11.5-13.4)</td>
<td>12.3±3.1 (11.3-13.4)</td>
<td>12.6±3.8 (11.3-14.0)</td>
<td>13.9±3.0 (12.8-15.0)</td>
<td>15.4±2.1 (14.7-16.1)</td>
<td>15.9±2.7 (15.0-16.9)</td>
</tr>
</tbody>
</table>

Values are mean ± SD and (95% CI)

AP: antero-posterior, mVel: mean velocity, ML: medio-lateral
Levene’s Tests showed no homogeneity of variance while Shapiro-Wilk test indicated a normal distribution of the independent and dependent variables.

Compared to healthy controls, a significant difference ($p \leq 0.01$) in mVel was present in pain sufferers beginning at an NRS score of 3 in ML direction. This difference became highly significant ($p \leq 0.001$) from pain intensities 6-8. In AP direction, statistical significance ($p \leq 0.05$) was also reached at a pain intensity of 3 with an increase in significance from 5 to 8 ($p \leq 0.001$) (Figure 9.3).

**Figure 9.3:** Relationship between pain intensity and mean sway velocity in AP and ML

The horizontal line and the grey area indicate the mean score of healthy controls and the standard deviations respectively. The vertical lines indicate standard deviations, the boxes show mean and 95% CIs respectively.

Levels of significance compared to controls: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$
Compared to healthy controls, a significant difference in 90% circle diameter was only present at NRS scores of 6, 7 and 8 ($p \leq 0.001$) (Figure 9.4).

**Figure 9.4:** Relationship between pain intensity and 90% circle diameter

The horizontal line and the grey area indicate the mean score of healthy controls and the standard deviations respectively. The vertical lines indicate standard deviations, the boxes show mean and 95% CIs respectively.

Levels of significance compared to controls: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

The differences in postural sway between pain scores as assessed by Games-Howell are presented in Tables 9.5 and 9.6. With regards to mVel differences between the individual pain scores, significance was reached at lower NRS scores in ML compared to AP direction (Table 9.5).
Table 9.5: Sway differences between the NRS-11 scores for mVel AP and ML

<table>
<thead>
<tr>
<th>NRS-11 score</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tr>
<td>8</td>
<td>***</td>
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<td>7</td>
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<td>***</td>
<td>***</td>
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<td>***</td>
<td>n.s.</td>
</tr>
<tr>
<td>6</td>
<td>*</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
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<tr>
<td>5</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
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<td>n.s.</td>
</tr>
<tr>
<td>4</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>3</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>2</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
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<td>n.s.</td>
</tr>
</tbody>
</table>

ML    AP  ML  AP  ML  AP  ML  AP  ML  AP

n.s.: not significant ($p>0.05$), - : not possible
Levels of significance: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

Finally, the relative differences between pain scores for the parameter 90% circle diameter are demonstrated in Table 9.6. The same trend as seen with mean sway velocity can be observed. However, at pain intensities 2 and 3, significant differences between pain scores are present at larger intervals (3 NRS scores compared to 1-2 at mVel ML/AP).

Table 9.6: Sway differences between the NRS-11 scores for 90% circle diameter

<table>
<thead>
<tr>
<th>NRS-11 score</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
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<tr>
<td>8</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>*</td>
<td>n.s.</td>
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<tr>
<td>7</td>
<td>***</td>
<td>***</td>
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<td>**</td>
<td>*</td>
<td>n.s.</td>
</tr>
<tr>
<td>6</td>
<td>*</td>
<td>n.s.</td>
<td>n.s.</td>
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<tr>
<td>5</td>
<td>n.s.</td>
<td>n.s.</td>
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</tr>
<tr>
<td>4</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
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<tr>
<td>3</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
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<td>n.s.</td>
</tr>
<tr>
<td>2</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

ML    AP  ML  AP  ML  AP  ML  AP  ML  AP

n.s.: not significant ($p>0.05$), - : not possible
Levels of significance: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$
9.4.7. Regression analysis

The SPSS Curve Estimation function showed that a linear relationship was the most suitable line of fit (p<0.001). Hence, linear regression was used for further analyses of the data. No collinearity between the variables was determined.

The univariate regression analysis included the variables gender, age, weight, height, previous pain duration and pain intensity. With the exception of previous pain duration, all other independent variables exhibited a significant effect on mVel AP/ML and 90% circle diameter and were consequently included in the multivariate analysis. Of those, only pain intensity exhibited a significant effect on the selected COP parameters.

Mean velocity
The regression analysis for pain intensity was a fairly good fit, describing 53.0% of the variance in mVel ML and 40.0% in mVel AP (R²adj=51.0% and R²adj=38.4% respectively), the overall relationship was highly significant in both ML and AP direction (F=244.1, p<0.001 and F=140.7, p<0.001 respectively). Mean sway velocity increased by 1.53 mm/s for every extra pain level in ML (β=0.70, T=14.7), and by 1.27 mm/s for every extra pain level in AP direction (β=0.59, T=11.1).

90% circle diameter
The regression equation for pain intensity was a poor fit, describing just 18.7% of the variance in velocity moment (R²adj=16.5%). The overall relationship, however, was highly significant (F=47.7). The 90% circle diameter of the COP excursion increased by 0.6 mm for every extra pain level (β=0.40, T=6.4).
9.4.8. Main sway direction

There was a significant trend towards predominant sway in ML direction with increasing pain intensity as described by the COP parameter "Main sway axis". The data provided is based on three recordings of 77 participants (total n=231) (Figure 9.5).

Figure 9.5: Main sway direction of healthy controls compared to NSLBP sufferers

Levels of significance compared to healthy controls: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

9.5. Discussion

We were unable to enroll a sufficient number of patients per pain intensity group to allow analysis of all 10 NRS scores. This may be explained by the fact that those with a pain intensity of 1 do not feel enough discomfort to seek chiropractic care while patients with NRS
scores of 9 and higher are not commonly encountered in a chiropractic practice as the potential severity of the condition warrants medical attention instead.

Our data demonstrated a linear relationship between pain intensity and postural sway velocities in both AP and ML direction. The increase of 1.53 mm/s (ML) and 1.27 mm/s (AP) per NRS score corresponds in more practical terms to an increase in sway velocity of about 14% in both ML and AP direction when taking data from healthy controls as a reference.

This basic observation is in full agreement with a general observation by Lihavainen et al. [287] who conducted a similar study in a geriatric population. They did not, however, investigate the postural sway related to the individual pain scores but reached their conclusions based on a subdivision into mild or moderate/severe pain only.

In contrast, Kuukkanen et al. [174], were unable to identify an association between pain and postural sway. This may be explained by the fact that they also did not find significant differences between pain patients and healthy controls to begin with, probably due to the low average pain intensities mentioned in their study. Most recently, Maribo et al. [288] were also unable to detect a relationship between pain and COP excursions. Apart from issues associated with the experimental setup and patient characteristics, the patient cohort (n=96) did not contain an equal distribution of pain intensities. Therefore, extreme postural sway readings due to inter-subject variability may have affected the overall results.

While in AP direction a significant increase sway velocity started at a lower pain score, the overall difference compared to healthy controls was similar to that in ML direction. On the other hand, the ML sway velocity increased at a faster rate. In addition, this study confirms the altered postural sway characteristics previously reported in NSLBP sufferers [1], where a higher COP mVel and larger sway area compared to healthy controls was described.
However, we were unable to confirm higher sway velocities in AP compared to ML direction previously reported [174, 177]. In contrast, our results indicate higher mVel ML for all pain intensities and it is difficult to determine why opposite results were reached. A reason solely associated with the lower sampling durations applied in those studies (20sec) appears insufficient. Data from healthy controls in the reliability pilot study (Table 7.1.2) indicates that while single trials of 90sec durations show about 10% lower mVel ML compared to recordings at 30sec (11.0mm/s compared to 12.3mm/s), sway in AP direction remained unaffected by the sampling duration. Factors associated with pain cannot be commented on as unfortunately neither Kuukkanen et al. [174] nor Hamaoui et al. [177] reported on the specific pain intensities of their participants (Table 3.4).

The non-overlapping 95% CI associated with NRS scores at higher pain intensities, particularly with mVel AP/ML, are surprising and may be attributable to our standardized experimental setup and selection of participants. Such a clear subdivision appears unlikely at first sight due to the inherently varying pain perception between individuals.

As the parameter 90% circle diameter is exclusively used with the Metitur system, it is not possible to put the respective results into context. However, it corresponds to the various parameters applied in the literature to describe COP sway area and may therefore offer at least limited comparability.

It appears likely that an equally linear relationship between 90% circle diameter and pain intensity also exists (Figure 9.4).

Our data, however, does not allow for an explanation of the underlying mechanism of the observed pain associated alterations in COP sway velocity. However, as previous pain
duration did not exhibit a significant effect on postural sway while the pain intensity did, this may suggest that pain interference [165] may be the determining factor.

Recently, Hodges advanced this concept to a new theory that proposes complementary, additive or competitive adaptations of the motor system during pain [289]. This was concluded based on earlier findings that such adaptations appear to be task dependent and may involve increased activity of muscles [290], decreased activity [291], or a combination of both [292]. Such a redistribution of activity may also occur within a muscle [293]. It has been shown that while the discharge rate of active motor units is reduced during experimental pain, the overall force output was maintained due to recruitment of additional, otherwise not active units [293]. These observations oppose the idea of a uniform “pain inhibition” of the motoneuron pool.

However, it has to kept in mind that for these experiments the motor recruitment pattern were investigated by EMG during voluntary, active movements. They do not necessarily reflect those employed involuntarily during static task conditions. Secondly, the nature of selective muscle actions observed on EMG (e.g. transversus abdominis [196]) may not necessarily correlate with the multifactorial COP excursions. In the light of these findings it may therefore be assumed that inhibitory functions are predominate in quiet stance where maintaining balance is the only postural requirement and no additional muscular recruitment is necessary.

Neuro-physiological changes, on the other hand, are rather dependent on pain duration and therefore a significant time effect would have been expected. Future studies assessing postural sway before and after acute pain stimulation or using analgesics in chronic and acute NSLBP patients may add valuable information in this respect.

Furthermore, as no other studies have looked into the relationship between a broader range of pain intensities and COP measures it is not possible to compare our results with others.
At lower and medium pain intensities there was no apparent change in the COP parameters. This may be due to participants finding it difficult to decide on their "true" score [294], NRS-5 for example shows the widest standard deviations across all parameters. This may therefore explain why no statistically significant differences were observed between lower pain scores (NRS 2-4) for most parameters and may account at least partially for the variability in the associated COP measurements. However, as the confidence intervals across all pain scores remain fairly consistent, the variability of the postural sway measurements most likely reflects individual variations within the COP excursions. The results also suggest that the neurological alteration previously described [161, 166-168, 196] may only have an impact on COP measures at medium to high intensities (i.e. NRS≥5).

With regards to the observed significant trend towards predominant ML sway with increasing NRS-scores, the way the 360° circle was subdivided has to be considered (See Chapter 8, Figure 6.6). Consequently, there were quite a few borderline results that would have counted towards the other direction had the result varied by a degree or two. Nevertheless, the highly significant differences associated with higher pain scores suggest that the method employed did not alter the observed trend (Figure 9.5). The reason for this shift in sway direction, however, remains unclear.

The results show that factors such as previous pain duration and short term learning effects exhibit no effect on postural sway. Furthermore, and in contrast to other studies [12, 105, 146-148], no significant effect of age, height or weight on COP excursions could be demonstrated. This may be attributed to the demographics and physical characteristics of the participants as well as our COP measurement protocol. Consequently, no normalization process as described in Chapter 2 was applied to the COP data in order to remove linear trends.
The increased postural instability observed in our study is unlikely to be associated with attentional effects such as distraction from the postural task or, in contrast, with demanding particular attention. It has been shown that performing cognitive tasks during COP recordings causes a decrease in postural sway [295, 296], thereby showing the opposite effect to our pain related observations.

This leaves conscious or unconscious pain avoidance strategies as a contributing factor for the increased COP excursions. First of all, pain perception exceeding the intensity identified in our studies to cause postural sway alterations are not per se associated with such an effect. A postural response occurs only if structures involved in maintaining postural control (e.g. neck, low back or legs) are affected. Painful stimuli to the arms [180] or hands [195], for example, does not increase postural instability, while pain in the feet does [195]. Generally, an effect of pain avoidance cannot be fully excluded. However, no trend of increasing sway with discomfort was observed across the three repetitions or reported by the patients. The differences between the recordings remained not significant.

The results were derived using a protocol based on best evidence [92], nevertheless future studies are needed to confirm these findings by using the same protocol.

9.5.1. Clinical considerations

The COP measurement protocol used in this study may be suitable as an objective outcome measure for clinical monitoring purposes. However, the results would pose the question as to whether a reduction in pain intensity would also be associated with a decreased postural sway. Secondly, given the linear relationship between pain intensity and, for example, mVel, a clinically significant decrease of two points on a pain NRS [297] is equivalent to a reduction in
mean sway velocity of 3.6 mm/s in ML and of 3.0 mm/s in AP direction. It remains to be seen if such a reduction is also clinically significant.

In addition, this study indicates that any sample size calculations for COP measurements involving pain sufferers will have to consider the respective perceived intensity. Depending on the research purpose, the inclusion criteria may focus on those with NRS-scores of 5 or higher to reach significance compared to controls more readily.

The reliability of the results from our symptomatic patients proved to be very similar to those obtained from healthy controls (compare Chapter 7.1), which underlines the suitability of the selected experimental setup.

Increased postural sway has been reported to be closely associated with falls in a geriatric population [1, 298, 299]. Routine COP measurements of elderly patients may therefore allow the identification of high-risk patients and facilitate decision process for preventive measures such as balance training or therapeutic interventions. In addition, the results of this study highlight the potential benefits analgesic treatments in this context to lower postural instability.

Finally, the results may cast a new light on the interpretation of studies that reported no significant differences in postural sway between symptomatic individuals and healthy controls. In those instances (e.g. Brumange et al. [182] and Mok et al. [178]), these observations may be attributable to the low perceived pain intensities of the patients enrolled (compare Chapter 3, Table 3.2).
9.5.2. Limitations

One limitation of this study is the selection of COP parameters, one of which is not commonly used (90% circle diameter). Our inquiries about the formulae used to generate the parameters were not provided by the manufacturer due to restrictions in their commercial confidence policy. However, mVel is not only the most commonly used COP parameter in the literature but has shown to be both highly discriminative for NSLBP and reliable as outlined earlier. The parameter 90% circle diameter may be regarded as an appropriate descriptor of the area covered by the sway path. It may be therefore concluded that the data provided offers a sufficiently broad and detailed description of the COP excursions.

There is also the possibility that different pain perceptions between younger and older participants may have affected the combined results. The decrease in pain perception described in the literature [300], however, was demonstrated in a geriatric population and is unlikely to affect adults under 50 years of age. This nevertheless prohibits our results to be generalized to geriatric patients.

While significant differences in postural sway compared to healthy controls could be demonstrated in our patient population, the overall number of participants per NRS score was still comparably small.

In addition, comorbidity may have exhibited an effect of the results as some patients may not have reported all presenting complaints.

Finally, in addition to any inherent differences in balance ability between participants it also is possible that some of the patients underwent proprioceptive training in the past, probably as
part of a rehabilitation program. This might also affect the results, although such an effect is unlikely to exhibit significance.

9.6. Conclusions

Irrespective of the subjective nature of pain perception and the unclear causative factors, the results of this study show that COP sway velocity and perceived pain intensity of over 4 on an NRS scale appear closely related in adults with NSLBP of less than 50 years of age. This trend, while less obvious, is also apparent for the parameter 90% circle diameter. Routine COP measurements during the rehabilitation or treatment process may therefore offer an objective insight into the managing progress of a NSLBP patient.
ON THE RELATIONSHIP BETWEEN PAIN INTENSITY AND POSTURAL SWAY IN PATIENTS WITH NON-SPECIFIC NECK PAIN

CHAPTER 10

On the relationship between pain intensity and postural sway in patients with non-specific neck pain

10.1. Background

As outlined in Chapter 4, altered sway pattern with an increased postural instability are well documented in patients suffering from non-specific neck pain (NSNP) [301], the theories regarding the underlying mechanisms remain the same as described for those suffering from NSLBP (Chapter 9).

In the previous Chapter, a linear relationship between the magnitude of COP excursions and the perceived pain intensity was described in patients suffering from NSLBP. However, it is not known whether this relationship also exist in patients with NSNP. So, in order to compare postural sway between different painful areas, it would be of interest to apply the same ‘best-practice’ experimental setup on a group of NSNP sufferers.

Such a comparison may allow insights into whether anatomical differences between different body regions, e.g. in proprioceptive density, may be associated with differences in sway at identical pain intensities. A comprehensive analysis is presented later on in Chapter 13.

As with the previous study, the aim was to investigate whether postural sway is affected by the perceived pain level and whether factors such as age [12, 105, 148], gender, weight [147], height [146] or previous pain duration exhibit a significant effect on postural sway.
10.2. Materials and methods

10.2.1. Participants

We aimed at enrolling a minimum of 70 participants in both the symptomatic and the control group. Previous sample size calculations for a group of controls and symptomatic patients with an NRS-11 score of 4.8±2.4 using an Altman Nomogram [280] suggested recruitment of around 50 symptomatic and healthy participants each. However, in order to compensate for potential dropouts a higher number of participants was included.

Inclusion criteria for the symptomatic participants were NSNP of any duration and the presence of pain ≥2 on the NRS-11 scale at the time of the postural sway recordings. Participants were excluded if pain radiated further than the shoulder; there were positive nerve root findings, any condition that might affect balance (e.g. whiplash associated disorder or vestibular pathologies) or previous significant injuries such as traumatic damage to the spine. No pain medication was allowed within 24 hours prior to the recordings. Participants were also excluded if they were unable to perform the postural sway recording either due to any reason.

10.2.2. Procedures

To allow for comparison, the methods and procedures used here remain the same as applied in our previous study when assessing NSLBP patients (Chapter 9). Three consecutive recordings of 90sec duration were performed in narrow stance with eyes closed. The participants were instructed to stand as still as possible, keep the head erect and the arms at the sides. One minute breaks were allowed between trials.
10.3. Data analysis

10.3.1. Reliability

To test the reliability of the COP measures, a two-way mixed-effect intra-class correlation coefficient (ICC2,k) as described by Shrout et al. [138] was computed using absolute agreement. In addition, the SEM and 95% confidence intervals (CI) were calculated. The following criteria were used: 0.0-0.39 poor, 0.40-0.59 fair, 0.60-0.74 good and 0.75-1.00 excellent [277].

10.3.2. Pain intensity

Stepwise univariate regression analysis was conducted to assess for the possible effect of the following variables: age, gender, weight, height, pain intensity and previous pain duration on COP mVel AP/ML and 90% circle diameter. Those showing significance were included in the multivariate regression analysis. To investigate the appropriate form of regression analysis, the SPSS Curve Estimation function was applied to a scatter plot for pain intensity (independent variable) and the COP parameters (dependent variables).

We used Levene statistic to test for homogeneity of variance. Shapiro-Wilk test was conducted for all independent variables and the dependent variables separately per pain group to test for normality. The COP data was further analyzed using the Games-Howell test. Means, SDs and 95% CIs were calculated for all dependent variables. In addition, the collinearity diagnostics were applied. The level of statistical significance was set at $p \leq 0.05$. 
10.3.3. Main sway direction

As outlined in Chapter 9, the main sway direction was assessed based on the COP parameter "direction of main axis". The 360° circle was subdivided into two sections: Section 1 consisted of the 90° angles facing front and backwards (AP), Section 2 covered the angles left and right (ML).

10.4. Results

10.4.1. Participants

We were unable to recruit the required number of 10 patients for NRS scores 9 (n=3) and 10 (n=0). Seventy-five individuals suffering from NSNP initially volunteered to participate in this study. Five symptomatic participants were excluded for reporting that their severe pain affected their ability to maintain quiet stance (n=2), exhibiting an antalgic posture when standing (n=1), being unable to complete the trial due to general loss of balance (n=1) or boredom (n=1). This left a total of 70 NSNP sufferers to which a matching number of healthy controls with regards to their physical characteristics was enrolled (Figure 10.1).
The characteristics of the participants with non-specific neck pain are shown in Table 10.1.

Table 10.1: Demographic and functional characteristics

<table>
<thead>
<tr>
<th></th>
<th>NSNP (n=70)</th>
<th>Healthy controls (n=70)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>37.0±8.3</td>
<td>37.2±9.0</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>177.0±8.5</td>
<td>177.8±6.9</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>76.4±11.0</td>
<td>78.1±9.7</td>
</tr>
<tr>
<td>BMI</td>
<td>24.1±2.5</td>
<td>24.9±3.0</td>
</tr>
<tr>
<td>NRS-11 (0-10)</td>
<td>4.9±2.0</td>
<td>N/A</td>
</tr>
<tr>
<td>Previous pain duration (weeks)</td>
<td>16.6±23.3</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Values are mean ± SD, * compared to control groups

NSNP: non-specific neck pain

10.4.2. Reliability

The COP measurements for the neck pain sufferers were assessed for their reliability. With three recordings being averaged, excellent reliability (ICC2,k≥0.75) with narrow CIs was
reached. The data for mVel ML and mVel AP showed an ICC\(2,k\) of 0.85 (95% CI 0.79-0.90, SEM 1.70) and 0.90 (95% CI 0.86-0.94, SEM 1.36) respectively. The parameter 90% circle diameter reached an ICC\(2,k\) of 0.84 (95% CI 0.77-0.89, SEM 1.24).

10.4.3. Relationship between pain intensity and postural sway

Patients suffering from NSNP exhibited a greater postural instability than healthy controls signified by an increased mean sway velocity and sway area. A linear increase in sway velocity (mVel) in antero-posterior (AP) and medio-lateral (ML) direction, as well as for the 90% circle diameter was observed (Table 10.2).

**Table 10.2:** Pain intensity and postural sway at baseline

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>Pain intensity (NRS-11)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 (n=10)</td>
</tr>
<tr>
<td>mVel ML (mm/s)</td>
<td>10.5±2.2 (9.7-11.4)</td>
</tr>
<tr>
<td>mVel AP (mm/s)</td>
<td>8.9±1.9 (8.2-9.6)</td>
</tr>
<tr>
<td>90% circle diameter (mm)</td>
<td>10.4±1.6 (9.8-11.0)</td>
</tr>
</tbody>
</table>

Values are mean ± SD and (95% CI). AP: antero-posterior, mVel: mean velocity, ML: medio-lateral

Compared to healthy controls, a highly significant difference (\(p\leq0.001\)) in mVel was present in pain sufferers beginning at an NRS score of 5 in ML direction. A statistical significance (\(p\leq0.05\)) was reached in AP direction at pain intensity of 3 with an increase to high significance.
from 5 to 8 ($p \leq 0.001$) (Figure 10.2). Generally, there is a trend towards larger 95% CI and SD with higher pain scores, particularly in AP direction.

**Figure 10.2:** A box plot of the relationship between pain intensity and mean sway velocity in AP and ML.

![Box plot](image)

The horizontal line and the grey area indicate the mean score and the standard deviations of healthy controls. The vertical lines indicate standard deviations, the boxes show mean and 95% CIs respectively.

Levels of significance compared to controls: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

Compared to healthy controls, a significant difference in 90% circle diameter started at pain intensity 2 were the NSNP patients showed an decreased sway area compared to the controls (Figure 10.3). The postural sway results associated with this NRS score are significantly lower compared to healthy individuals ($p \leq 0.05$). Beginning at NRS level 3 a steady increase in 95%...
circle diameter can be observed. The difference compared to asymptomatic controls reached high statistical significance at NRS scores of 6, 7 and 8 ($p \leq 0.001$).

**Figure 10.3:** Relationship between pain intensity and 90% circle diameter

The horizontal line and the grey area indicate the mean score and the standard deviations of healthy controls. The vertical lines indicate standard deviations, the boxes show mean and 95% CIs respectively.

Levels of significance compared to controls: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

With regards to mVel differences between the individual pain scores, significance was reached more readily in ML compared to AP direction (Table 10.3). At higher pain intensities, no significant differences in postural sway could be observed between NRS scores.
**Table 10.3:** Sway differences between the individual NRS-11 scores for mVel AP and ML

<table>
<thead>
<tr>
<th>NRS-11 score</th>
<th>2</th>
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n.s.: not significant ($p>0.05$), - : not possible

Levels of significance: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

Table 10.4 shows the differences in postural sway between the various pain scores for the COP parameter 90% circle diameter. As with mVel AP/ML, there was no significant difference between the sway areas at higher pain intensities (NRS 6-7).

**Table 10.4:** Sway differences between the individual NRS-11 scores for 90% circle diameter

<table>
<thead>
<tr>
<th>NRS-11 score</th>
<th>2</th>
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</table>

n.s.: not significant ($p>0.05$), - : not possible

Levels of significance: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$
10.4.4. Regression analysis

Linear regression was used for further analyses of the data as the SPSS Curve Estimation function showed that a linear relationship was the most suitable line of fit (p<0.001).

The univariate regression analysis for the variables gender, age, weight, height, previous pain duration and pain intensity showed that pain intensity was the only significant effect for all selected parameters.

Mean velocity
The regression analysis for pain intensity was a fairly poor fit, describing 51.2% of the variance in mVel ML and 36.8% in mVel AP (R²adj=49.5% and R²adj=34.6% respectively), the overall relationship was highly significant in both ML and AP direction (F=192.1, p<0.001 and F=88.5, p<0.001 respectively). Mean sway velocity increased by 1.67 mm/s for every extra pain level in ML (β=0.68, T=12.8), and by 1.20 mm/s for every extra pain level in AP direction (β =0.50, T=8.4).

90% circle diameter The regression equation for pain intensity was a poor fit, describing 39.7% of the variance in velocity moment (R²adj=38.0%). The overall relationship, however, was highly significant (F=117.7, p<0.001). The 90% circle diameter of the COP excursion increased by 0.93 mm for every extra pain level (β =0.57, T=10.0).
10.4.5. Main sway direction

As previously observed in NSLBP sufferers, NSNP patients also exhibited a significant trend towards predominant sway in ML direction with increasing pain intensity. The data provided is based on three recordings of 70 symptomatic participants (total n=210) (Figure 10.4).

Figure 10.4: Main sway direction of healthy controls compared to NSNP sufferers

Levels of significance compared to healthy controls: * p≤0.05, ** p≤0.01, *** p≤0.001

10.5. Discussion

We were able to demonstrate a linear relationship between pain intensity and postural sway. This study further confirms the altered postural sway characteristics previously reported in NSNP sufferers [301] (Chapter 4), where a higher COP mVel and larger sway area compared to healthy controls was described.
The reason that we were unable to enroll the required number of patients experiencing the highest pain intensities (NRS 9-10) was probably that such individuals seek medical care instead of attending a chiropractic practice, as previously seen in NSLBP patients (Chapter 9).

In AP direction, a significant increase in sway velocity compared to healthy controls started at lower pain intensities (NRS 3 compared NRS 5 in ML direction), while the ML sway velocity increased at a faster rate. With regards to 90% circle diameter, a significant difference in terms of a larger sway area started at an NRS score of 5. Unfortunately, a comparison of this parameter to other studies is not possible as it is exclusively used with the GB300 forceplate. Furthermore, as no other studies have looked into the relationship between a broader range of pain intensities and COP measures it is not possible to compare our results.

However, our data allows a better insight into the interpretation of studies that curiously reported no significant differences in postural sway between symptomatic individuals and healthy controls (e.g. Field et al. [208]). In those instances, the observations may be attributable to low perceived pain intensities of the patients enrolled.

The linear trend between pain intensity and COP excursions observed in this study is very similar to results obtained from non-specific low back pain patients with an identical experimental setup [217]. However, the data from neck pain sufferers shows higher variability in the results. At similar COP mean values, both SDs and 95% CIs were larger for all NRS scores. This was most obvious at higher pain intensities where CIs were about twice as wide.

To appreciate the results of this study and possible clinical implications, a closer look at what may be responsible for the increased postural sway is necessary. The larger COP excursions observed here may be associated with the abundant cervical sensory receptors in joints and muscles [302, 303] as well as their central and reflex connections to visual, vestibular and...
postural control systems [304]. This may render the neck particularly prone to effects of nociceptive stimuli which would explain the increased sway rates compared to NSLBP patients.

However, considering the low sample size per NRS score (n=10) the interpretation of any difference warrants caution. For example, inter-subject variability in pain perception may have affected the results. The significantly lower 90% circle diameter of NSNP patients at NRS-2 compared to the control group (n=70) illustrates this (Figure 10.3).

Furthermore, three important aspects seem to point towards "pain interference" rather than the damage or impairment of proprioceptive structures as the causative factor for the reported larger COP excursions.

Firstly, Vuillerme et al. demonstrated that inducing pain in healthy individuals instantly triggered altered sway pattern. At an average pain intensity of VAS 7.1 (SD 1.7), the postural sway velocity climbed from 11.3 mm/s to around 17.0 mm/s [210]. This result is very similar to our observations at a comparable pain severity level (Table 10.2, Figure 10.2).

Secondly, Treleaven et al. were unable to identify patients with chronic whiplash associated disorder (WAD) where damage to proprioceptive structures would be expected. They tested these patients by using COP total path length under various testing conditions. However, when they used wavelet analysis they were able to discriminate WAD cases from healthy controls [305]. In this type of analysis signal data is converted into coefficients that capture information about the signal at locations and for different frequencies [207]. Although a single recording of 30 seconds may have limited the reliability of the data [92], this nevertheless indicates that traditional parameters such as mVel or area may only be sensitive to larger sway alterations associated with certain degrees of pain perception. Unfortunately, Treleaven et al. did not
report pain levels in this study. However, as the sway values were very similar to those reported in a study with an identical setup and pain at VAS 2.8-4.1 [202], the pain intensity are probably similar. These pain scores are associated with early and minor sway alterations (Figure 10.2), the difficulty to detect changes in the COP excursions may therefore be explained.

Our results also show that factors such as previous pain duration and short term learning or fatigue effects exhibited no effect on postural sway. Furthermore, and in contrast to other studies [105, 134, 147, 306], we could not demonstrate any significant effect of age, height or weight on COP excursions. This may be attributed to the demographics and physical characteristics of our participants. Although Chiari et al. [307] demonstrated a relationship between height and the magnitude of the COP excursions in subjects between 150cm and 190cm, the fairly low variability in height found in our participants (177.0±8.5cm) may explain why no significant correlation could be identified. The same is true with regards to age related alterations as other relevant studies [105, 134] employed elderly participants older than 60yrs. Our study had a cut-off age of 50yrs. Finally, when Hue et al. [147] investigated body weight as a predictor of postural sway, the close association identified was based on a very wide weight range from 59.2-209.5kg while ours was quite narrow at 76.4±11.0kg. Consequently, no normalization of the COP data as outlined in Chapter 2 was conducted to remove linear trends.

As with NSLBP, the increased postural instability observed in this study is unlikely to be associated with attentional effects, fatigue or conscious/unconscious pain avoidance strategies as discussed in Chapter 9.
10.5.1. Clinical considerations

The linear relationship between pain intensity and postural sway indicates that COP measurements may be suitable as a discreet objective outcome measure for clinical monitoring purposes. Based on this, we will explore in later chapters whether the linear trend observed in NSNP and NSLBP patients is maintained if pain scores change in recovering patients. This may allow an insight into the postural consequences of altering pain levels, despite any inter-subject variability in perception of nociceptive stimuli.

The results further pose the question as to whether a reduction in pain intensity would also be associated with a decreased postural sway. Secondly, given the linear relationship between pain intensity and, for example, mVel, a clinically significant decrease of two points on a pain NRS [20] is equivalent to a reduction in mean sway velocity of about 3-4 mm/s. As with NSLBP patients, it remains to be seen if such a reduction is also clinically significant. This question will be addressed in Chapters 14 and 15.

This study shows that any sample size calculations for COP measurements involving pain sufferers will have to consider the perceived intensity of the participants. Depending on the research purpose, the inclusion criteria may focus on those with NRS-scores of 5 or higher to reach significance compared to controls more readily.

The reliability of the data obtained from our symptomatic patients and the fact that all participants completed the trials without reporting difficulties underlines the suitability of the selected experimental setup. In addition, the reliability results suggests that the results are unaffected by fatigue or learning over the course of the three repetitions.
One direct clinical implementation of our results may be the conduction of COP measurements to identify malingerers, particularly if both the purpose of the test as well as the normal values are unknown to the subjects. Even if the individual is aware that pain is associated with greater COP excursions, a study with pseudo-malingerers showed that imitating pain related sway pattern is difficult at best. When trying to actively exhibit greater postural sway, the average results for sway velocity and sway area greatly exceeded those expected from a real pain sufferer [206].

10.5.2. Strengths and limitations

The major strength of this study is the best practice experimental setup that ensured reliable data collection and showed no short-term effects of fatigue and learning effects throughout the three recordings. Our inclusion and exclusion criteria further prohibited our overall results from being affected by demographic or anthropometric factors.

Pain perception between younger and older patients varies and a decrease in pain perception in geriatric individuals has been described [300]. Although this does not affect our sample groups with a cut-off age of 50yrs, it nevertheless prohibits our results to be generalized to elderly patients.

While significant differences in postural sway compared to healthy controls could be demonstrated in our patient population, the overall number of participants per NRS score was still comparably small. As discussed before, our results are therefore prone to be affected by extreme COP measures. Other sample groups with identical NRS scores may therefore show varying results. However, the linear trend is expected to be preserved. Similar studies with an
identical experimental setup and larger sample sizes should be conducted to confirm our results.

10.6. Conclusions

Irrespective of the subjective nature of pain perception and the unclear causative factors, the results of this study show that COP sway velocity and perceived pain intensity of over 4 on an NRS scale appear closely related in adults less than 50 years of age. This trend is also apparent for the parameter 90% circle diameter. Although routine COP measurements during the rehabilitation or treatment process may offer an objective insight into the managing progress of a NSNP patient, more research into the clinimetrics of the tool needs to be undertaken.
THERE IS A RELATIONSHIP BETWEEN PAIN INTENSITY AND POSTURAL SWAY IN PATIENTS WITH NON-SPECIFIC MID BACK PAIN
CHAPTER 11

There is a relationship between pain intensity and postural sway in patients with non-specific mid back pain

11.1. Background

In the previous chapters we have demonstrated the linear relationship between pain intensity and postural sway measures in NSLBP and NSNP patients. The collection of data from patients with non-specific mid back pain (NSMBP) will conclude the postural sway analyses of the three painful regions.

Mid-back pain is a common occupational health issue with a one-year prevalence between 3.0-55.0% with most occupational groups showing medians at around 30% [306]. The same theories regarding the underlying mechanisms for pain related sway alterations apply as described in Chapters 9 and 10.

This is the first study to investigate postural sway in patients with non-specific mid-back pain using a best practice experimental setup.

11.2. Materials and methods

The methods used here are generally the same as applied in the previous studies assessing NSLBP and NSNP patients (Chapters 9 and 10). This is based on best practice as well as it will allow for direct comparisons between the three spinal regions.
11.2.1. Participants

The sample size calculations for a group of controls and symptomatic patients with an average NRS-11 score of 3.8±1.8 using an Altman Nomogram [280] suggested the recruitment of around 200-300 symptomatic and healthy participants each. However, the linear relationship previously identified in NSLBP and NSNP patients suggested that a lower number would be sufficient considering the low average pain intensity in the group the sample size calculations were based on.

The aim was to include 10 patients within each NRS group from 2 to 8, giving a total of 70 NSMBP sufferers. In addition, an age-matched control group of identical size was to be recruited. The same inclusion and exclusion criteria previously stated in Chapters 9 and 10 applied here as well.

11.2.2. Procedures

The same procedures from the NSLBP and NSNP studies (see Chapters 9 and 10) were used to assess the NSMBP sufferers. In short, a physical examination was conducted on all participants and their pain intensity scores were recorded prior to the COP measurements. Based on best practice, three successive trials of 90 seconds with 60 seconds resting period between each trial. The participants were asked to remove their shoes and stand upright with a narrow stance on the calibrated forceplate. Eyes had to be closed, the head erect and their arms hanging loosely by their sides.
11.3. Data analysis

The mean sway velocity (mVel) in ML and AP direction was chosen as the main COP parameter. In addition, 90% circle diameter was included as a descriptor of the sway area.

11.3.1. Reliability

To test the reliability of the COP measures, a two-way random-effect intra-class correlation coefficient (ICC$_{2,k}$) was calculated from an average of three consecutive measures using absolute agreement. In addition, SEM and 95% confidence intervals were computed. As before, the following criteria were used: 0.0-0.39 poor, 0.40-0.59 fair, 0.60-0.74 good and 0.75-1.00 excellent [277].

11.3.2. Pain intensity and postural sway

As with the previous studies, a stepwise univariate regression analysis was conducted to investigate the effect of age, gender, weight, height, pain intensity and previous pain duration on the COP parameters. Variables that showed statistical significance were included in the following multivariate regression analysis. To investigate the appropriate form of regression analysis, the SPSS Curve estimation function was applied to a scatter plot for the independent variables and the COP parameters (dependent variables).

Levene's test was included to test for homogeneity of variance and Shapiro-Wilk test for all independent variables and the dependent variables separately per pain group to test for normality. The COP data was further analyzed using the Games-Howell test to investigate
difference between the individual NRS groups. Means, SDs and 95% CIs were calculated for all dependent variables. In addition, the collinearity diagnostics were conducted. The level of statistical significance was set at $p \leq 0.05$.

11.3.3. Main sway direction

The main sway direction was assessed based on the "direction of main axis" COP parameter described in Chapter 6.5.3.

11.4. Results

11.4.1. Participants

In total, 65 patients suffering from NSMBP volunteered to participate in this study. Following the physical examination, two patients were excluded for the suspicion of an underlying cardiovascular condition (n=1) and reporting that the severity of their discomfort was affecting their ability to maintain quiet upright stance (n=1). This left 63 participants with 9 patients in each NRS group. To these, a matching number of healthy controls were enrolled (Figure 11.1). As in the previous studies, a sufficient number of patients could not be recruited for the NRS 9 (n=3) and NRS 10 group (n=0) and therefore limited the inclusion to NRS 2-8.
The characteristics of all participants are presented in Table 11.1.

### Table 11.1: Demographic and functional characteristics

<table>
<thead>
<tr>
<th></th>
<th>NSMBP (n=63)</th>
<th>Healthy controls (n=63)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>34.8±7.9</td>
<td>36.4±8.5</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176.4±7.2</td>
<td>177.3±7.0</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>76.1±8.4</td>
<td>78.3±9.1</td>
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<tr>
<td>BMI</td>
<td>24.4±1.6</td>
<td>24.6±2.4</td>
</tr>
<tr>
<td>NRS-11 (0-10)</td>
<td>5.0±2.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Previous pain duration (weeks)</td>
<td>24.8±40.0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Values are mean ± SD

NSMBP: non-specific mid-back pain

#### 11.4.2. Reliability

When three recordings were averaged, COP data reached excellent reliability (ICC₂,k≥0.75) with narrow CIs and SEM values. The results for mVel ML and AP demonstrated an ICC₂,k of
0.87 (95% CI 0.80-0.91, SEM 1.33) and 0.85 (95% CI 0.85-0.95, SEM 1.23) respectively. The parameter 90% circle diameter reached an ICC2,k of 0.79 (95% CI 0.72-0.85, SEM 1.33).

### 11.4.3. Relationship between pain intensity and postural sway

Compared to healthy controls, patients with NSMBP exhibited an increased mean sway velocity and sway area. This was further signified by a linear increase in sway velocity in both AP and ML direction as well as for the 90% circle diameter (Table 11.2).

#### Table 11.2: Pain intensity and postural sway at baseline

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>2 (n=9)</th>
<th>3 (n=9)</th>
<th>4 (n=9)</th>
<th>5 (n=9)</th>
<th>6 (n=9)</th>
<th>7 (n=9)</th>
<th>8 (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mVel ML (mm/s)</td>
<td>10.4±1.8 (9.7-11.1)</td>
<td>10.0±2.3 (9.1-10.9)</td>
<td>11.3±2.5 (10.3-12.3)</td>
<td>14.3±2.6 (13.3-15.4)</td>
<td>15.9±3.5 (13.3-18.6)</td>
<td>15.4±2.5 (14.4-16.3)</td>
<td>17.1±3.4 (15.8-18.5)</td>
</tr>
<tr>
<td>mVel AP (mm/s)</td>
<td>9.9±2.1 (9.1-10.8)</td>
<td>8.9±1.8 (8.2-9.5)</td>
<td>9.8±2.6 (8.8-11.3)</td>
<td>12.5±3.2 (11.3-13.8)</td>
<td>12.9±4.5 (9.6-16.4)</td>
<td>11.9±2.3 (11.0-12.8)</td>
<td>14.5±2.8 (13.4-15.6)</td>
</tr>
<tr>
<td>90% circle diameter (mm)</td>
<td>11.5±2.0 (10.7-12.3)</td>
<td>10.7±2.1 (9.6-11.7)</td>
<td>12.3±2.8 (11.2-13.4)</td>
<td>13.6±2.5 (12.6-14.6)</td>
<td>13.4±3.3 (12.1-14.7)</td>
<td>14.4±3.1 (13.1-15.6)</td>
<td>15.1±2.5 (14.1-16.0)</td>
</tr>
</tbody>
</table>

Values are mean ± SD and (95% CI). AP: antero-posterior, mVel: mean velocity, ML: medio-lateral

Levene’s Tests showed no homogeneity of variance while Shapiro-Wilk test indicated a normal distribution of the independent and dependent variables.

Compared to healthy controls, a statistically significant difference (p≤0.001) in mVel was present in pain sufferers beginning at an NRS score of 5 in both ML and AP direction. Particularly in mVel AP, patients reporting a pain intensity of NRS 6 showed very large 95% CI and SDs (Figure 11.2).
Figure 11.2: Relationship between pain intensity and mean sway velocity in AP and ML

The horizontal line and the grey area indicate the mean score and the standard deviations of healthy controls. The vertical lines indicate standard deviations, the boxes show mean and 95% CIs respectively.

Levels of significance compared to controls: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

At NRS level 3 a decrease in 90% circle diameter was observed ($p>0.05$) that changed to a significantly larger diameter compared to healthy controls at pain intensities of NRS $\geq 5$. The 95% CI and SD remained fairly similar for all pain scores (Figure 11.3).
Figure 11.3: Relationship between pain intensity and 90% circle diameter

The horizontal line and the grey area indicate the mean score and the standard deviations of healthy controls. The vertical lines indicate standard deviations, the boxes show mean and 95% CIs respectively.

Levels of significance compared to controls: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

As a general trend, significant differences in postural sway between the individual NRS scores were reached at lower pain intensities in AP compared to ML direction. At higher pain intensities (NRS 5-7), significant differences in postural sway could only be observed when compared to NRS 8 (Table 11.3).
Table 11.3: Sway differences between the individual NRS-11 scores for mVel AP and ML

<table>
<thead>
<tr>
<th>NRS-11 score</th>
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</table>

n.s.: not significant (p>0.05), - : not possible

Levels of significance: * p≤0.05, ** p≤0.01, *** p≤0.001

Table 11.4 shows the differences in postural sway between the various pain scores for the COP parameter 90% circle diameter. Generally, a significant difference between NRS scores is reached about every two levels.

Table 11.4: Sway differences between the individual NRS-11 scores for 90% circle diameter

<table>
<thead>
<tr>
<th>NRS-11 score</th>
<th>2</th>
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</tr>
</tbody>
</table>

n.s.: not significant (p>0.05), - : not possible

Levels of significance: * p≤0.05, ** p≤0.01, *** p≤0.001
11.4.4. Regression analysis

Linear regression was used for further analyses of the data as the SPSS Curve Estimation function showed that a linear relationship was the most suitable line of fit (p>0.001).

The initial univariate regression analysis including the variables gender, age, weight, height, previous pain duration and pain intensity showed that the latter was the only exhibiting a significant effect on the COP parameters.

Mean velocity

The regression analysis for pain intensity was a poor fit, describing 45.1% of the variance in mVel ML and 23.5% in mVel AP (R²adj=44.8% and R²adj=23.1% respectively). The overall relationship was highly significant in both ML and AP direction (F=153.35, p<0.001 and F=57.5, p<0.001 respectively). Mean sway velocity increased by 1.25 mm/s for every extra pain level in ML (β=0.67, T=12.4) and by 0.79 mm/s for every extra pain level in AP direction (β=0.48, T=7.6).

90% circle diameter

The regression equation for pain intensity was an equally poor fit, describing 20.3% of the variance in 90% circle diameter (R²adj=19.8%) while the overall relationship was highly significant (F=47.4, p<0.001). The circle diameter of the COP path increased by 0.65 mm for every extra pain level (β=0.45, T=6.8).
11.4.5. Main sway direction

A trend towards predominant sway in ML direction with increasing pain intensities can be observed starting at about NRS score 4. The data was based on three recordings of 63 participants (total n=189) (Figure 11.4).

![Figure 11.4: Main sway direction of healthy controls compared to NSMBP sufferers](image)

**Figure 11.4:** Main sway direction of healthy controls compared to NSMBP sufferers

Levels of significance compared to healthy controls: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

11.5. Discussion

This is the first study investigating changes in postural sway associated with NSMBP. As with NSLBP and NSNP, a linear relationship between the pain intensity and the COP parameters can be observed. The underlying mechanisms have been discussed in detail in Chapter 9 and 10.
and will not be repeated here. There are, however, some aspects specific factors associated with NSMBP that need to be addressed.

At lower pain intensities (NRS 2-4), no significant difference compared to healthy controls was present. Beginning at NRS 5, however, a steep increase in mVel AP/ML was measured with large associated SD and 95% CI values. This is particularly apparent at NRS 6.

In addition to normal inter-subject variability in pain perception, the location and origin of the pain appears to exhibit an important effect on the COP excursions in NSMBP sufferers. This may be due to the fact that we did not limit the inclusion criteria for discomfort in the thoracic region to pain in the spinal area, but instead included all causes of pain in the whole mid back including the chest wall.

Secondly, our deliberate classification of the whole trunk from spinal level from T12 to T4 as "mid back" may have played a role as the pain location is often not limited to one region. Due to the anatomy of the back, pain in the thoraco-lumbar junction may have been classified as mid back pain but, due to its muscular connections, potentially affect lumbar structures as well. The same accounts for the cervico-thoracic junction where according to generally accepted definitions, the neck extends town to T4 vertebral level [275].

Previous research has further demonstrated the effect of respiration on postural sway [175, 176, 308]. During quiet breathing, trunk and lower limb movements in phase with the respiration counteract the disturbances of postural stability due to chest and abdominal expansion [309], a mechanism that varies between individuals [310]. Both slow and fast breathing have shown an association with increased COP excursions in chronic LBP patients when compared to normal quiet respiration [175]. It was hypothesized that restricted
segmental motion may disturb the normal phasic compensatory trunk and lower limb movements counteracting the respiratory disturbance [311].

In a more recent study, Smith et al. [179] showed that although trunk movement is reduced during experimentally induced muscle pain (NRS 4.4, SD 1.9), this is not associated with increased displacement of the COP in conjunction with normal respiration. In symptomatic state, their participants showed normal breathing and expansion of rib cage and abdomen. This indicates that patients with impaired chest and abdominal expansion in conjunction with pain and mechanical restrictions may exhibit an additional increase in postural sway excursions.

When reviewing the examination findings of patients enrolled, it became apparent that several of those reporting higher pain intensities (NRS 6-8) presented with pain of muscular origin and/or due to rib dysfunctions that radiated intercostally to the lateral or anterior chest (7/27, 26%). This is likely to cause altered breathing pattern and disturb the normal phasic compensatory trunk and lower limb movements counteracting the respiratory disturbance [311]. Three of those patients were in the NRS 6 group, which may at least partially account for the large variability in the COP measures observed. Therefore, an additional, not pain-related contributing factor for the altered postural sway may have been introduced that is difficult to quantify and adjust for. Depending on the research purpose, such clinical presentations may be added to the exclusion criteria.

When conducting post hoc analysis excluding the patients with intercostal pain in the NRS 6 group (n=3), the postural sway measures changed to 14.5mm/s (95% CI 12.5-15.9) for mVel ML, 12.7mm/s (95% CI 10.1-14.2) for mVel AP and 13.1mm (95% CI 12.1-14.3) for 90% circle diameter. Normally, removing participants from an already small sample size (n=9) increases variability. However, in this case removing these participants with impaired breathing (3/9,
33%) narrowed the 95% CIs. Although coincidence cannot be excluded due to the small remaining sample size (n=6), this indicates that patients with impaired breathing should have been excluded from participation.

11.5.1. Clinical considerations

In addition to the clinical consideration discussed in the previous chapters, the fact that the pain origin and location was not further specified in the thoracic region may have introduced an additional, not pain-related effect on postural sway as discussed above. For future studies, data sets from patients whose pain is associated with altered breathing pattern or respiratory difficulties should not be analyzed together with and compared to participants where this is not the case.

11.5.2. Strengths and limitations

The general strengths and limitations already discussed for the NSLBP and NSNP studies also apply here. In addition, the impact of impaired respiration needs to be considered as outlined above.

11.6. Conclusions

As with the previous painful regions, COP excursions and the pain intensity of NRS ≥4 appear closely related in adults less than 50 years of age. Routine COP measurements of NSMBP patients undergoing treatment or rehabilitation may offer an objective progress assessment.
COMPARING COP EXCURSIONS OF PATIENTS WITH NON-SPECIFIC LOW BACK, MID BACK AND NECK PAIN
CHAPTER 12

Comparing COP excursions of patients with non-specific neck, mid-back and low back pain

12.1. Background

As previously demonstrated (Chapter 7.1), our sway data showed excellent reliability when three measures of 90sec duration were averaged. We have also demonstrated a linear relationship between postural sway and the pain intensity as assessed by NRS scores for all three painful spinal regions (Chapters 9-11). In addition, a shift towards predominant sway in ML direction was identified with increasing pain intensities for all three painful regions.

This chapter aims to identify similarities and differences in the COP excursions between NSLBP, NSNP and NSMBP sufferers as well as the main sway direction in relation to the pain intensities.

This is the first time that data from different symptomatic areas is comprehensively presented and compared based on a standardized, best practice experimental protocol. This way it may be possible to appreciate possible differences and similarities associated with their respective anatomy.
12.2. Materials and methods

The COP measures and sway direction results obtained during previous studies involving symptomatic patients with NSNP, NSLBP and NSMBP (Chapters 9-11) are analyzed and compared. The experimental procedures and patient characteristics have been described in detail in the respective chapters of this thesis. The participants completed three consecutive COP measurements of 90 sec duration with eyes closed in narrow stance.

12.3. Data analysis

With regards to pain intensity and postural sway, means, SDs and 95% CIs were calculated for all dependent variables. Independent samples t-tests were conducted to investigate difference in postural sway for the NRS scores between painful regions. The level of statistical significance was set at $p \leq 0.05$.

For describing the main sway direction, the main sway direction was assessed based on the COP parameter "direction of main axis" as outlined in Chapter 6.5.3.

12.4. Results

12.4.1. Participants

The postural sway data of 210 symptomatic individuals previously enrolled in the NSLBP (n=77), NSNP (n=70) and NSMBP (n=63) studies were analyzed and compared.
12.4.2. Pain intensity

The figures show that the COP excursions of all three symptomatic areas were similar. As a general trend, participants with NSMBP showed smaller COP excursions compared to those with NSLBP and NSNP (Figures 12.1 and 12.2).

**Figure 12.1:** Relationship between pain intensity and mean sway velocity in AP and ML

![Graph showing relationship between pain intensity and mean sway velocity in AP and ML](image)

The horizontal line indicates the mean score of healthy controls.

Symbols indicate mean scores of the symptomatic individuals.
Figure 12.2 shows the relationship between pain intensity and 90% circle diameter for the painful regions. Again, the results appear similar with the exception of the lower and higher pain scores (Figure 12.2).

**Figure 12.2:** Relationship between pain intensity and 90% circle diameter

![Graph showing relationship between pain intensity and 90% circle diameter](image)

The horizontal line indicates the mean score of healthy controls. Symbols indicate mean scores of the symptomatic individuals.

The following tables show the differences in postural sway measures between the three painful regions for the parameters mVel ML/AP and 90% circle diameter (Tables 12.1-12.3).

A total of 63 data sets were compared. As a general observation, the postural sway data for NSLBP and NSNP were very similar throughout the different pain intensities for all included
parameters. Only two COP results showed a significant difference (p≤0.001) for mVel AP at NRS score 6 and 90% circle diameter at NRS score 2.

Participants with NSMBP exhibited significantly different was characteristics compared to both NSLBP and NSNP patients at about a quarter of the COP measures (18/63, 28%) over a broad spectrum of NRS scores. This included lower sway velocities in AP and ML direction at both lower and higher pain intensities. For 90% circle diameter, a similar trend could be observed at NRS 2 and 3.

**Table 12.1**: Comparison of painful regions for the parameter mVel ML

<table>
<thead>
<tr>
<th>NRS Score</th>
<th>Painful region</th>
<th>p-values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSLBP</td>
<td>NSNP</td>
</tr>
<tr>
<td>8</td>
<td>21.2±3.5 (20.0-22.5)</td>
<td>20.0±5.7 (17.9-22.2)</td>
</tr>
<tr>
<td>7</td>
<td>18.6±2.4 (17.7-19.4)</td>
<td>19.1±3.9 (17.6-20.6)</td>
</tr>
<tr>
<td>6</td>
<td>15.6±2.6 (14.7-16.6)</td>
<td>17.0±3.1 (15.9-18.2)</td>
</tr>
<tr>
<td>5</td>
<td>13.9±3.7 (12.6-15.2)</td>
<td>13.7±3.8 (12.2-15.1)</td>
</tr>
<tr>
<td>4</td>
<td>13.1±3.1 (12.0-14.2)</td>
<td>11.8±2.5 (10.9-12.8)</td>
</tr>
<tr>
<td>3</td>
<td>12.4±2.8 (11.4-13.4)</td>
<td>11.7±2.4 (10.9-12.7)</td>
</tr>
<tr>
<td>2</td>
<td>11.5±2.2 (10.7-12.3)</td>
<td>10.5±2.2 (9.7-11.4)</td>
</tr>
</tbody>
</table>

Values are mean ± SD (95% CI)

NSLBP: non-specific low back pain, non-specific mid-back pain, non-specific neck pain
### Table 12.2: Comparison of painful regions for the parameter mVel AP

<table>
<thead>
<tr>
<th>NRS Score</th>
<th>Painful region</th>
<th>p-values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSLBP</td>
<td>NSNP</td>
</tr>
<tr>
<td>8</td>
<td>18.4±4.5</td>
<td>16.7±5.7</td>
</tr>
<tr>
<td></td>
<td>(16.8-20.0)</td>
<td>(14.6-18.9)</td>
</tr>
<tr>
<td>7</td>
<td>15.8±3.1</td>
<td>15.3±4.5</td>
</tr>
<tr>
<td></td>
<td>(14.7-16.9)</td>
<td>(13.6-17.0)</td>
</tr>
<tr>
<td>6</td>
<td>13.0±2.1</td>
<td>16.3±4.6</td>
</tr>
<tr>
<td></td>
<td>(12.2-13.7)</td>
<td>(14.6-18.1)</td>
</tr>
<tr>
<td>5</td>
<td>12.9±4.3</td>
<td>13.1±3.6</td>
</tr>
<tr>
<td></td>
<td>(11.3-14.4)</td>
<td>(11.8-14.5)</td>
</tr>
<tr>
<td>4</td>
<td>11.2±3.2</td>
<td>11.9±3.8</td>
</tr>
<tr>
<td></td>
<td>(10.1-12.4)</td>
<td>(10.4-13.2)</td>
</tr>
<tr>
<td>3</td>
<td>11.1±3.0</td>
<td>10.7±3.4</td>
</tr>
<tr>
<td></td>
<td>(10.1-12.2)</td>
<td>(9.5-12.0)</td>
</tr>
<tr>
<td>2</td>
<td>9.8±2.2</td>
<td>8.9±1.9</td>
</tr>
<tr>
<td></td>
<td>(9.0-10.6)</td>
<td>(8.2-9.6)</td>
</tr>
</tbody>
</table>

Values are mean ± SD (95% CI)

Overall, the COP parameter 90% circle diameter showed the fewest differences between the three painful regions (4/63, 6%) all of which occurred at NRS scores 2-3 (Table 12.3).

### Table 12.3: Comparison of painful regions for the parameter 90% circle diameter

<table>
<thead>
<tr>
<th>NRS Score</th>
<th>Painful region</th>
<th>p-values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSLBP</td>
<td>NSNP</td>
</tr>
<tr>
<td>8</td>
<td>15.9±2.7</td>
<td>16.1±3.8</td>
</tr>
<tr>
<td></td>
<td>(15.0-16.9)</td>
<td>(14.7-17.5)</td>
</tr>
<tr>
<td>7</td>
<td>15.4±2.1</td>
<td>15.7±2.0</td>
</tr>
<tr>
<td></td>
<td>(14.7-16.1)</td>
<td>(14.9-16.5)</td>
</tr>
<tr>
<td>6</td>
<td>13.9±3.0</td>
<td>15.0±3.0</td>
</tr>
<tr>
<td></td>
<td>(12.8-15.0)</td>
<td>(13.9-16.1)</td>
</tr>
<tr>
<td>5</td>
<td>12.6±3.8</td>
<td>13.2±2.4</td>
</tr>
<tr>
<td></td>
<td>(11.3-14.0)</td>
<td>(12.3-14.1)</td>
</tr>
<tr>
<td>4</td>
<td>12.3±3.1</td>
<td>12.1±2.3</td>
</tr>
<tr>
<td></td>
<td>(11.3-13.4)</td>
<td>(11.3-13.0)</td>
</tr>
<tr>
<td>3</td>
<td>12.4±2.6</td>
<td>12.5±2.3</td>
</tr>
<tr>
<td></td>
<td>(11.5-13.4)</td>
<td>(11.6-13.3)</td>
</tr>
<tr>
<td>2</td>
<td>12.3±2.2</td>
<td>10.4±1.6</td>
</tr>
<tr>
<td></td>
<td>(11.5-13.1)</td>
<td>(9.8-11.0)</td>
</tr>
</tbody>
</table>

Values are mean ± SD (95% CI)
12.4.4. Main sway direction

There was a trend towards predominant sway in ML direction with increasing pain intensities for all three painful regions. Very similar results were observed across the NRS scores, particularly at intensities 3, 5 and 8 (Figure 12.3).

Figure 12.3: Main sway direction of healthy controls compared to pain sufferers

Symbols indicate mean scores of the symptomatic individuals.

12.5. Discussion

Patients with NSLBP and NSNP exhibit very similar postural sway with respect to the pain intensity. The significant differences observed at two pain scores can be attributed to high...
inter-subject variability that lead to higher mean scores in mVel AP at NRS 2 (NSLBp) and 90% circle diameter at NRS 6 (NSNP). The results also deviate from the obvious linear trend otherwise observed in the respective painful region (Tables 12.2 and 12.3).

The comprehensive results of three studies allow us to conclude the following:

Firstly, as all three studies that enrolled a total of 120 participants (30 per NRS group) show very similar results, this strengthens our basic observation regarding the presence of a linear relationship between the pain intensity and COP excursions.

Secondly, it appears that there are generally no statistically significant differences between the three painful regions at medium pain intensities. Considering the low number of participants per NRS group (n=9-11), inter-subject variability as well as the fact that at low pain intensities (NRS 2-3) the COP results of the symptomatic groups are located both above and below the mean values of healthy controls (Figures 12.1-12.2), it is also questionable whether a real difference at lower pain intensities exists. Consequently, COP measures are unsuitable for distinguishing between patients with pain in the three painful regions investigated here.

When comparing COP excursions associated with high pain intensities (NRS 7-8), participants with NSMBP exhibited lower postural sway velocities than NSNP and NSLBp patients. Due to the limited contribution of the thoracic spine to postural stability, this may be plausible as long as respiration remains unaffected (see Chapter 11). However, it may also be a consequence of high inter-subject variability in postural sway associated with our small sample sizes.

As discussed before, the interpretation of the results for main sway direction is complicated by the non-validated subdivision into sway quadrants applied here (Chapter 6.5.3). However, as
this is expected to affect the results obtained for all three areas equally, it appears that there are no significant differences between the main sway direction of the different painful regions.

12.6. Conclusions

Patients with NSNP, NSLBP and NSMBP generally show a similar linear relationship between pain intensity and postural sway. In addition, a trend towards predominant body sway in ML direction can be observed as pain intensity increases. Due to our small sample sizes per NRS score and inter-subject variability it remains unclear whether significant differences between the painful regions exist at medium and low intensities. At least at high NRS scores, however, patients with NSMBP exhibit smaller COP excursions compared to those with NSNP and NSLBP.
IS THERE A RELATIONSHIP BETWEEN DISABILITY AND BODY SWAY IN PATIENTS WITH NON-SPECIFIC NECK, MID-BACK OR LOW BACK PAIN?
CHAPTER 13

Is there a relationship between disability, pain intensity and body sway in patients with non-specific neck, mid back or low back pain?

13.1. Background

Persistent pain is often accompanied by functional impairments and it has been shown that pain intensity is a significant predictor of pain-related disability [312-314]. Scudds et al. [313], for example, observed that pain of severe or greater intensity was significantly associated with disability. Gronblad et al. [315] reported evidence for a significant relationships between the perceived disability and pain intensity in patients with low back, leg and buttocks pain. More recently, clear trends towards linear relationships between pain intensity and disability scores were also described in other studies [160, 316].

Previously a relationship between pain intensity and COP sway was described in patients with NSLBP, NSNP and NSMBP. This study aims to investigate whether similar linear relationships between the perceived level of disability and pain as well as the COP excursions exist for any or all of the three anatomical regions (neck, mid-back, low back).

This is the first study to comprehensively address the question above by comprehensively investigating disability for different painful areas.
13.2. Materials and methods

13.2.1. Participants

A total of 217 patients with non-specific neck (n=70), mid-back (n=63) and low-back pain (n=77) volunteered to participate in this study. The characteristics of the participants are shown in Table 13.1.

Table 13.1: Demographic and functional characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>NSLBP (n=77)</th>
<th>NSNP (n=70)</th>
<th>NSMBP (n=63)</th>
<th>Healthy controls (n=77)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>37.2±8.2</td>
<td>37.0±8.3</td>
<td>34.8±7.9</td>
<td>39.1±11.4</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.6±6.9</td>
<td>177.0±8.5</td>
<td>176.4±7.2</td>
<td>179.7±7.7</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>79.5±10.6</td>
<td>76.4±11.0</td>
<td>76.1±8.4</td>
<td>80.1±9.8</td>
</tr>
<tr>
<td>BMI</td>
<td>24.8±2.6</td>
<td>24.1±2.5</td>
<td>24.4±1.6</td>
<td>24.7±3.1</td>
</tr>
<tr>
<td>NRS-11 (0-10)</td>
<td>5.0±2.1</td>
<td>4.9±2.0</td>
<td>5.0±2.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Previous pain duration (weeks)</td>
<td>19.2±31.4</td>
<td>16.6±23.3</td>
<td>24.8±40.0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Values are mean ± SD

NSLBP: non-specific low back pain, NSNP: non-specific neck pain, NSMBP: non-specific mid back pain

13.2.2. Disability assessment

The perceived disability of the participants was assessed by a German version of the DRI [246]. The tool was chosen as it is a global questionnaire, allowing the assessment and comparison of disability levels perceived by patients with pain in different areas of the body. The DRI involves 12 items of everyday activities presented as VAS-100 scales (Chapter 6.4.4.1). Thereby, possible associations between DRI scores, pain intensity and the magnitude of COP excursions can be identified.
13.2.3. Procedures

The participants received the German version of the DRI together with an introductory cover sheet describing the DRI and showing a filled out sample. The translation process was conducted as described in Chapter 6.4.4. Sufficient time for the completion of the DRI was allocated in a separate, quiet room prior to the COP recordings. Questions were answered by clinic staff as required or forwarded to be addressed by the patient's chiropractor.

The scoring of the DRI was conducted by AR and TB who measured the VAS scales, added up the mm and expressed the final scores as a number between 0 (no disability) and 1200 (full disability).

13.3. Data analysis

13.3.1. Disability

Stepwise univariate regression analysis was conducted to assess for the possible effect of the perceived disability on COP mVel AP/ML, velocity moment, and 90% circle diameter. To investigate the appropriate form of regression analysis, the SPSS Curve Estimation function was applied to a scatter plot for disability (independent variable) and the COP parameters and pain intensity (dependent variables). In addition, the best-fit line was also investigated using logarithmic transformation. This procedure is applied to dampen exponential growth patterns and reduce heteroscedasticity (i.e., stabilizes variance) [317].

Means, SDs and 95% CIs were calculated for all dependent variables. F-tests were applied to investigate levels of significance between the three painful areas. The level of statistical significance was set at $p \leq 0.05$. 

256
13.4. Results

13.4.1. Participants

All participants were able to complete the DRI scales correctly and reported no difficulties understanding the questions. Out of the 210 participants, seven (3%) added additional handwritten comments to one or more of the VAS scales. As this was not considered to affect the ratings itself, these forms were included for analysis.

13.4.2. Relationship between physical disability and postural sway

Generally, the DRI ratings remained in the lower half of the DRI scale (≤600/1200) for all painful regions, even at high NRS scores.

13.4.2.1. Non-specific low back pain patients

The following table shows the reported disability levels associated with NRS scores 2-8 in NSLBP patients (Tables 13.2).

<table>
<thead>
<tr>
<th>Pain intensity (NRS-11)</th>
<th>2 (n=11)</th>
<th>3 (n=11)</th>
<th>4 (n=11)</th>
<th>5 (n=11)</th>
<th>6 (n=11)</th>
<th>7 (n=11)</th>
<th>8 (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DRI</strong></td>
<td>160.7±141.8</td>
<td>80.8±31.2</td>
<td>143.8±160.5</td>
<td>219.6±213.7</td>
<td>326.2±129.7</td>
<td>373.5±200.3</td>
<td>506.5±177.2</td>
</tr>
<tr>
<td></td>
<td>(65.5-256.0)</td>
<td>(59.9-101.8)</td>
<td>(36.0-251.6)</td>
<td>(76.1-363.2)</td>
<td>(239.1-413.3)</td>
<td>(238.9-508.0)</td>
<td>(387.4-625.5)</td>
</tr>
</tbody>
</table>

Values are mean ± SD and (95% CI)
With the exception of NRS score 3 which shows comparably low DRI scores and narrow 95% CIs, the results show a clear linear relationship between the two variables (Figure 13.1).

Figure 13.1: Disability associated with NSLBP of varying intensity

The vertical lines indicate standard deviations, the boxes show mean and 95% CIs respectively.

13.4.2.2. Non-specific neck pain patients

Table 13.3. shows the relation between the DRI scores and the pain intensity in neck pain sufferers. While a steep incline in disability with great variability can be observed at NRS score 5, the values for pain intensity 6 are very low.
Table 13.3: Disability associated with NSNP of varying intensity

<table>
<thead>
<tr>
<th></th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
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<tbody>
<tr>
<td>(n=10)</td>
<td>(n=10)</td>
<td>(n=10)</td>
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<td>(n=10)</td>
<td>(n=10)</td>
<td>(n=10)</td>
<td>(n=10)</td>
</tr>
<tr>
<td>DRI</td>
<td>76.6±71.5</td>
<td>91.0±34.7</td>
<td>73.8±44.7</td>
<td>220.8±195.4</td>
<td>109.8±63.1</td>
<td>263.7±117.3</td>
<td>266.9±144.2</td>
</tr>
<tr>
<td></td>
<td>(25.4-127.8)</td>
<td>(66.2-115.8)</td>
<td>(41.8-105.8)</td>
<td>(81.0-360.6)</td>
<td>(64.4-154.6)</td>
<td>(179.8-347.6)</td>
<td>(163.7-370.0)</td>
</tr>
</tbody>
</table>

Values are mean ± SD and (95% CI)

This visual presentation of the data above allows a better appreciation of the small DRI scores reported by those experiencing pain intensity 6 in this study (Figure 13.2).

Figure 13.2: Disability associated with NSNP of varying intensity

The vertical lines indicate standard deviations, the boxes show mean and 95% CIs respectively.

13.4.2.3. Non-specific mid-back pain patients

The results of NSMBP patients indicate a fairly linear relationship between DRI scores and pain intensity (Table 13.4).
### Table 13.4: Disability associated with NSMBP of varying intensity

<table>
<thead>
<tr>
<th>Pain intensity (NRS-11)</th>
<th>DRI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n=9)</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>50.0±60.7</td>
</tr>
<tr>
<td></td>
<td>(3.2-96.6)</td>
</tr>
</tbody>
</table>

*Values are mean ± SD and (95% CI)*

The variability in DRI scores observed in this group of NSMBP patients showed the greatest variability at NRS score 6.

### Figure 13.3: Disability associated with NSMBP of varying intensity

![Disability associated with NSMBP of varying intensity](image)

The vertical lines indicate standard deviations, the boxes show mean and 95% CIs respectively.

### 13.4.3. Regression analysis

Linear regression was used for further analyses of the data as the SPSS Curve Estimation function showed that a linear relationship was the most suitable line of fit for all groups of pain...
sufferers (p<0.001). In addition, logarithmic transformation of the disability scorings were conducted. As this showed a curved line, linearity was assumed.

The univariate regression analysis for the variable disability showed a significant effect on the selected COP parameters and pain intensity for either patient group.

13.4.3.1. COP excursions, pain and disability scores of NSLBP patients

Mean velocity

The regression analysis for disability was a poor fit, describing 30.9% of the variance in mVel ML and 24.5% in mVel AP (R²adj=30.6% and R²adj=24.2% respectively). The overall relationship was highly significant in both ML and AP direction (F=102.6, p<0.001 and F=74.4, p<0.001 respectively). Disability scores increased by 26.2 points for every extra mm/s in mVel ML (β=0.56, T=10.1), and by 24.0 points for every extra mm/s in AP direction (β =0.50, T=8.6).

90% circle diameter

Here, the regression equation was a very poor fit, accounting for just 10.9% of the variance in circle diameter (R²adj=10.5%). The overall relationship, however, was also highly significant (F=28.1, p<0.001). The DRI scores increased by 21.7 points for every extra mm in 90% circle diameter (β =0.33, T=5.3).

Pain intensity

Again, the regression equation for disability was a poor fit, describing 39.0% of the variance in circle diameter (R²adj=38.6%). The overall relationship was highly significant as well (F=145.5, p<0.001). The DRI scores increased by 64.5 points for every extra NRS score (β=0.62, T=12.1).
13.4.3.2. COP excursions, pain and disability scores of NSNP patients

Mean velocity
The regression analysis for disability was a very poor fit again, describing 25.1% of the variance in mVel ML and 10.8% in mVel AP (R²adj=24.0% and R²adj=10.0% respectively), however, the overall relationship was highly significant in both ML and AP direction (F=22.8, p<0.001 and F=8.2, p<0.001 respectively). Disability levels increased by 12.3 points for every mm/s in mVel ML (β=0.50, T=4.8), and by 8.7 points for every extra mm/s in mVel AP direction (β =0.33, T=2.9).

90% circle diameter
The regression equation for disability was a very poor fit again, describing 9.7% of the variance in circle diameter (R²adj=8.4%) while the overall relationship was significant (F=7.3, p=0.009). The DRI scores increased by 13.3 points for every extra mm in 90% circle diameter (β =0.31, T=2.7).

Pain intensity
Again, the regression equation for disability was a poor fit, describing 39.0% of the variance in circle diameter (R²adj=38.6%). Again, the overall relationship was highly significant (F=145.5, p<0.001). The DRI scores increased by 64.5 points for every extra NRS score (β =0.62, T=12.1).
13.4.3.3. COP excursions, pain and disability scores of NSMBP patients

Mean velocity
The regression analysis for disability as assessed by the DRI was a poor fit, describing 25.2% of the variance in mVel ML and 17.5% in mVel AP ($R^2_{\text{adj}}=24.8\%$ and $R^2_{\text{adj}}=17.1\%$ respectively), the overall relationship was highly significant in both ML and AP direction ($F=63.2$, $p<0.001$ and $F=39.8$, $p<0.001$ respectively). Disability increased by 27.4 points for every extra increase in mm/s in mVel ML ($\beta=0.50$, $T=7.9$), and by 26.0 points for every extra mm/s in mVel AP direction ($\beta=0.42$, $T=6.3$).

90% circle diameter
The regression equation for disability was a very poor fit, describing just 10.3% of the variance in circle diameter ($R^2_{\text{adj}}=9.8\%$). The overall relationship, however, was highly significant ($F=21.5$, $p<0.001$). The disability score increased by 22.3 points for every extra mm in 90% circle diameter ($\beta=0.32$, $T=4.6$).

Pain intensity
As with mVel, the regression equation was a poor fit, describing 36.4% of the variance in velocity moment ($R^2_{\text{adj}}=36.1\%$) with the overall relationship being highly significant ($F=107.0$, $p<0.001$). The disability as assessed by the DRI increased by 60.9 points per extra NRS score ($\beta=0.60$, $T=10.3$).
13.5. Discussion

With regards to the COP excursions, linear relationships were present between all parameters and the DRI scores, although the regression equations were poor fits throughout and the results varied greatly between the different painful regions. Logarithmic transformations were performed for all data sets and showed to be worse fits. Therefore, linearity was assumed. Of all parameters, sway area was the poorest descriptor of DRI scores.

A similar relationship could be observed between DRI and NRS scores. This interaction appears plausible as more pain is expected to cause increased disability in everyday activities. It has to be kept in mind though that disabilities associated neither with pain nor the presenting functional complaint may have influenced the DRI scorings (e.g. due to age related changes).

The average DRI scorings remained in the lower 50% of the scale (≤600/1200). As the patients reported mild to severe pain (NRS 2-8) and the age range was 18-50yrs, a broader spread of DRI scores would have been expected. Consequently, the validity of the data obtained for this thesis appears questionable and warrants caution in interpretation.

This does not, however, question the general suitability of the DRI for such research purposes as the age of the participants (≤50 years) and inter-subject variability due to the small sample sizes per NRS score may play a predominant role here. Larger patient groups including elderly participants may produce the expected spread over a broader range of DRI scores.

While those with NSLBP and NSMBP presented a fairly clear linear trend, this was less obvious for NSNP patients, where particularly at NRS score 6 surprisingly low DRI scores were reported. Again, inter-subject variability associated with the small sample size may
account for this observation. As the regression analysis showed a similar linear relationship between DRI scores and pain intensity and the NSNP patients showed COP excursions reflecting this (Table 10.2), there is no apparent reason why the associated DRI scores deviated so much from the expected values.

As with all other data entries, the calculation of the overall DRI scores were repeated twice and no error was identified. Mistakes or misinterpretations filling out the questionnaires cannot be excluded, however, this appears unlikely as a fairly equal distribution of such mistakes would be expected across the pain groups. More likely, inter-subject variability associated with the small number of participants (n=10) may be the determining factor here.

All painful regions showed the greatest variability in disability at medium pain scores. Patients with NSMBP, however, exhibited greater variability in DRI scores at high pain intensities than NSNP and NSLBP sufferers (Table 13.3). This may be explained by the fact that patients with simple mid-back pain were mixed with those reporting limited chest expansion, impaired respiration and associated additional discomfort. The latter also perceived greater pain intensities (Chapter 11.5).

In conjunction with the data from the pain studies, these results further underline the need for pain control due to the close correlation with disability in everyday activities. While the sample sizes were sufficient for postural sway measures, the number of patients per NRS score turned out to be insufficient for disability analysis. Although this limits the validity of the DRI results, it remains unclear whether a different disability assessment tool would have served better under these circumstances.
13.6. Strengths and limitations

The simplicity of the DRI ensured that all participants understood the questions and were able to complete the questionnaire correctly. The best practice experimental setup for the COP measures constitutes another major strength of study.

However, one of the limitations of this study is that patients were not asked for functional impairments not associated with their current complaint that may have influenced their overall disability rating. As with the previous studies, the results involving pain ratings were also prone to be affected by the low number of participants per NRS group. This may have further complicated the identification of linearity.

13.7. Conclusions

The results of this study indicate a linear relationship between disability and the COP excursions and, consequently, pain ratings. However, the results varied greatly between the different painful regions and inter-subject variability associated with the small number of participants appears to have affected the results. While the general clinical value of the DRI cannot be commented on, it appears that a wider range of scorings may be obtained with significantly larger sample sizes.
IS THERE A RELATIONSHIP BETWEEN PAIN AND THE MAGNITUDE OF COP EXCURSIONS FOLLOWING NON-SPECIFIC THERAPEUTIC INTERVENTIONS IN NSLBP PATIENTS?

Published as: Ruhe A, Fejer R, Walker BF. Is there a relationship between pain and the magnitude of COP excursions following non-specific manual interventions in patients with non-specific low back pain? BMC Musculoskeletal Disorders, under review.
CHAPTER 14

Is there a relationship between pain and the magnitude of COP excursions following non-specific manual interventions in NSLBP patients?

14.1. Background

In Chapter 9 we outlined that NSLBP intensity is correlated with the magnitude of postural sway. This poses the question as to whether a) this relationship is maintained in case of pain reduction in this case associated with a manual therapeutic intervention and b) whether the resulting altered pain intensities correlate with similar COP measures compared to those perceived by other participants pre-intervention.

As the previous literature reviews suggested, there is some evidence for "pain interference" as described by Crombez et al. [165] to be the predominate causative factor for the increased COP excursions in pain sufferers [216, 301] (Chapter 3.1 and 9.5). Decreasing pain perception by whatever means may therefore reduce postural sway. So far, the question regarding the underlying mechanism has not been answered conclusively. This study sets out to contribute to this discussion by investigating possible sway alterations associated with pain relief over a short time period that makes any reversal of neuro-physiological changes unlikely.

Analgesic effects have been described for a variety of manual therapeutic interventions such as spinal manipulation, mobilization or soft tissue techniques. The mechanisms by which spinal manipulative therapy (SMT) may produce hypoalgesia and restoration of biomechanical
function are not well understood, and there is limited evidence regarding the neuro-
physiological effects of spinal manipulation. There is, for example, still the unresolved
controversy as to whether the mode of action behind the analgesic effects of manipulation is
confined to spinal levels or involves a more complex, supraspinal mechanism [318].

DeVocht et al. [319] noted a reduction of resting electromyographic EMG activity after SMT
which is consistent with and supportive of studies suggesting that tight muscle bundles are
associated with low back pain and that these can be alleviated by SMT [320, 321]. It has been
further proposed that the neurophysiologic pathway of this EMG response to the SMT involves
the activation of mechanoreceptors in structures such as zygapophyseal joint capsules [322],
spinal ligaments, intervertebral discs, the cutaneous receptors, muscle spindles and golgi
tendon organs [322-325]. These afferent discharges may activate inhibitory interneurons to
inhibit alpha motoneuron pools of the paraspinal musculature [273].

The literature review by Vernon [326] reported that mechanical spinal pain may produce
disturbances in sensory processing by sensitizing the dorsal horn neurons, resulting in a
lowered threshold of excitation [327, 328]. In such a "central facilitated state" [329], otherwise
innocuous stimuli may produce pain. In this context, spinal manipulation is thought to exhibit
an ameliorative effect that reduces this hypersensitivity [327], a process believed to be
associated with the activation of mechanocreceptors as described above.

The gate control theory of Melzack et al. [330] also stressed the active role of the dorsal horn
of the spinal cord. Non-noxious mechanical inputs such as resulting from high velocity, low
amplitude (HVLA) thrusts that are transmitted via large, myelinated A fiber neurons can inhibit
the response of dorsal horn neurons to nociceptive stimuli from C fibers [331]. Central
transmission of pain can be blocked by increased proprioceptive input and facilitated by a lack
of proprioceptive input. This nonspecific mechanism explains why pain can be relieved by
nociceptive stimulation at another site [328] and why rubbing an acutely painful area alleviates the pain [332].

Furthermore, forceful muscle stretching induces presynaptic inhibition of afferents from the skin [333], thereby influencing pain producing mechanisms and breaking the cycle of pain, muscle spasm and immobility which predominates in many cases of low back pain [273].

In addition, other possible mechanisms of spinal manipulation involving biochemical factors such as plasma β-endorphin levels that are thought to participate in the physiology of anti-nociception have been suggested [334].

As with manipulation, the clinical efficacy of mobilization procedures for pain reduction has been reported in the literature [335, 336]. However, the physiologic mechanisms remain equally unclear, although mobilization has shown to elicit a profound but transient attenuation of motor neuron activity similar to that observed in HVLA manipulations [337, 338].

As this study was conducted in a private clinical setting that required payment for the interventions, for ethical reasons no control group receiving placebo treatments could be enrolled.

We hypothesized that a pain change would also result in a change in postural sway. To our knowledge, this is the first study to investigate this clinical question with a best practice experimental setup for COP measurements.
14.2. Materials and methods

14.2.1. Participants

The participants of this study were those from a previously enrolled group of 77 NSLBP sufferers (see Chapter 9) to complete a course of three measurements and interventions. Based on their availability and willingness to participate this study aimed at enrolling around 40 participants for both symptomatic and an aged-matched control group.

After oral and printed information had been given, the subjects consented to participate in this study, which was approved by the Murdoch University Human Research Ethics Committee (Approval 2010/173). The cut-off age for both controls and symptomatic individuals was 50 years as after that age related impairments to postural stability could not be excluded [12, 105, 148].

Inclusion criteria for the symptomatic participants were NSLBP of any duration and the presence of pain ≥2 on the NRS-11 scale on the day of the postural sway recordings. The aim was to enrol a broad spectrum of pain intensities between NRS scores 2 and 8 as previously included in the pain intensity study (Chapter 9.4.1). Participants were excluded if the pain went below the gluteal fold, there were positive nerve root findings, serious spinal deformities or previous injuries. No pain medication was allowed within 24hrs prior to the recordings. Participants were also excluded if they were unable to perform the postural sway recording either due to pain or other reasons.

For the purpose of this study, healthy was defined as the absence of any self-reported neurological or musculoskeletal impairments, pain or disability for a minimum of 6 months prior to the time of evaluation. Specifically, individuals with a history of back pain within 6 months or previous injury to the neck or lower extremities, any known balance problems or the usage of
medication associated with pain suppression or altered sensory perception were excluded. The physical examination of the control group must also have ruled out any back or extremity complaints or significant biomechanical impairments that might influence the measurements.

14.2.2. Measurement equipment

As before, the system used for this study was a Metitur Good Balance GB300® CE (Metitur Oy, Finland). Signals were sampled at 100Hz, amplified and converted from analogue to digital. High frequency noise was reduced by a low-pass filter with a cut-off frequency of 10Hz.

14.2.3. Procedures

The experimental setup was based on an earlier literature review where a best practice setup with regards to the reliability of COP data was published [92]. Accordingly, trials were conducted with eyes closed as the data obtained shows higher reliability than with eyes open. Mean velocity (mVel) was chosen as the main COP parameter as this has consistently shown to be both reliable [92] and discriminative for NSLBP [216].

The participants were asked to remove their shoes and stand upright on the forceplate with their eyes closed, the head erect and their arms hanging loosely by their sides. The foot position was narrow stance with toes and heels touching. Three successive trials of 90 seconds duration each were conducted with a preceding 5 sec adaption period that was not recorded. The forceplate was calibrated prior to the recordings and further underwent an automatic calibration check before each trial.
Based on a physical examination, the participating NSLBP sufferers received a series of three non-specific therapeutic interventions consisting of a selection or a combination of all of the following: a) manipulation, b) mobilization, c) soft tissue techniques. The treatments were administered by two experienced chiropractors with 8 years of clinical practice each (TB and AS) at 2-3 day intervals and targeted the whole kinematic chain. They directly followed the COP measurements (Figure 14.1). Pain levels were assessed before each measurement session by an NRS-11 scale.

The practitioners performing the examination and delivering treatments were otherwise not involved in this study and blinded to the results of both the COP measures and the NRS-scores.

14.2.4. Data analysis

To assess changes in postural sway velocity and NRS-scores, means, SDs and 95% CIs were calculated for all dependent variables (COP parameters) per session and NRS group. Independent samples t-test was performed to analyze differences in postural sway between pain intensity groups across the three measurements. The level of statistical significance was set at $p \leq 0.05$.

14.3. Results

14.3.1. Participants

Seventy-seven participants participated in the initial measurement to provide baseline data (Chapter 9). From this group, 51 initially consented to participate in three measurements and
to receive a series of manual interventions. Thirty-eight individuals (75%) suffering from NSLBP completed the full course. The following factors accounted for the loss to follow-up: Significant pain relief after less than three interventions (n=3), unwillingness to participate in the COP measurements while continuing treatments (n=8), discontinuation of chiropractic care and referral to medical specialist (n=2). A matching number of controls were selected randomly from the overall 77 healthy participants enrolled in the NSLBP study. A comprehensive flowchart of procedures and participants is presented as Figure 14.1.

**Figure 14.1: Flowchart of procedures**

```
Initial number of participants with NSLBP (n=51) → 3-4 day interval →

**Session 1** n=51 (100%)
1) Physical examination
2) COP measurement
3) Therapeutic intervention

3-4 day interval →

**Session 2** n=51 (100%)
1) Physical examination
2) COP measurement
3) Therapeutic intervention

3-4 day interval →

**Session 3** n=38 (75%)
1) Physical examination
2) COP measurement
3) Therapeutic intervention

Random selection from n=77 healthy controls →

Healthy controls (n=38) → COP reference data from previous study (Chapter 9)

Loss to follow-up n=13 (25%)
Reasons:
- Referral to medical specialist (n=2)
- Significant pain relief prior to completion (n=3)
- Unwillingness to participate in measurements (n=8)

Statistical analysis
```
All participants were able to complete the trials without difficulty. The characteristics of the participants are shown in Table 14.1.

**Table 14.1: Patient characteristics**

<table>
<thead>
<tr>
<th>NSLBP intervention group (n=38)</th>
<th>Healthy controls (n=38)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>39.8±10.5</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.1±8.4</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>79.3±12.4</td>
</tr>
<tr>
<td>BMI</td>
<td>24.9±3.1</td>
</tr>
<tr>
<td>NRS-11 score at baseline</td>
<td>5.6±2.0</td>
</tr>
</tbody>
</table>

Values are mean ± SD

NSLBP: non-specific low back pain

**14.3.2. Pain intensity over the course of three therapeutic interventions**

There was a significant decrease in pain intensity at measurement three (2.9±1.6 (95% CI 2.2-3.3) compared to NRS 5.6±2.0 (95% CI 4.9-6.2) at baseline (p≤0.001). Figure 14.2 shows the individual NRS scores as well as the average pain intensities. Where an increase in pain perception was reported at measurement 3 compared to the previous session, the NRS-score was still lower compared to baseline.
Figure 14.2: Development of individual and mean NRS-scores over three measurements

One grey line may indicate pain scores of several participants.

14.3.3. Relationship between pain intensity and postural sway

All participants experienced pain relief over the course of the therapeutic interventions and all but two (2/38, 5%) exhibited lower associated postural sway velocities (Figure 14.3 and 14.4).
Figure 14.3: Individual changes in mVel ML and AP over three measurements (n=38)
The following figures show the relationship between pain intensity and postural sway for patients where the intervention did not result in pain reduction and the NRS scores changed less or equal to one score (n=7, 18%). Overall pain intensity remained nearly constant between NRS 4.5 (baseline) and NRS 3.8 (measurement 3). At the same time, mVel ML remained at around 13 mm/s and mVel AP at around 11 mm/s. Postural sway associated with higher pain intensity at baseline shows greater variation while those at lower NRS scores remained very similar (Figure 14.5 and 14.6).
Figure 14.5: Pain intensity and mVel ML for participants with a change in NRS scores of $\leq 1$ over the course of three measurements ($n=7$).

One grey line may indicate pain scores of several participants.
Figure 14.6: Pain intensity and mVel AP for participants with a change in NRS scores of ≤1 over the course of three measurements (n=7)

Figures 14.7 and 14.8 demonstrate changes in sway velocity associated with a reduction in pain intensity of ≥4 NRS scores in 9 participants (24%). The mean NRS score changed from 7.8 at baseline to 2.7 at measurement 3. Mean sway velocity ML decreased from 18.8 mm/s to 13.7 mm/s and mVel AP from 16.5 mm/s to 12.5 mm/s at the same time.
The lower two sway velocities shown in Figure 14.7 were recordings at the lower boundary expected in patients with NRS scores 7 and 8 (compare Chapter 9). Despite reporting lower pain scores overall, one participant exhibited a greatly increased sway velocity at measurement 3 compared to session 2 and generally showed high variability in the COP results (Figure 14.7).

**Figure 14.7:** Pain intensity and mVel ML for participants with a change in NRS scores of ≥4 over the course of three measurements (n=9)

One grey line may indicate pain scores of several participants
Figure 14.8 demonstrates the changes associated with decreasing NRS-scores for mean sway velocity in AP direction.

**Figure 14.8:** Pain intensity and mVel AP for participants with a change in NRS scores of ≥4 over the course of three measurements (n=9)

One grey line may indicate pain scores of several participants
The results of the independent sample t-tests showed that with few exceptions there were no significant differences between a) the results of the first measurement (baseline) and the reference data and b) between the COP excursions measured at session 2 and 3 compared to the reference values.

There were generally no statistically significant differences in postural sway measures between those who experienced a certain pain intensity at one of the follow-up sessions compared to patients perceiving a similar pain at baseline. This was true for all included COP parameters (Figure 14.2-14.4).

As a general trend, higher pain intensities at session 2 and 3 that were most likely reported by patients with the highest NRS scores at baseline (NRS 8) were associated with greater variability in postural sway compared to those associated with lower pain scores. As in contrast to medium and low pain intensities sway associated with NRS scores 6-8 showed mostly non-overlapping 95% CIs, observing sway data for these scores across the trials may offer particularly valuable insights. All patients reporting these NRS levels experienced pain relief and therefore no data sets were included twice for the same pain score. The respective values appear shaded in gray on the following tables (Tables 14.2-14.4).
Table 14.2: Results for postural sway velocity ML across three repeated measurements at 2-3 day intervals

<table>
<thead>
<tr>
<th>NRS score</th>
<th>Reference values</th>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>mVel ML</td>
<td>p-value</td>
</tr>
<tr>
<td>8</td>
<td>(20.0-22.5)</td>
<td>10</td>
<td>(18.8-22.0)</td>
<td>0.91</td>
</tr>
<tr>
<td>7</td>
<td>(17.7-19.4)</td>
<td>5</td>
<td>19.3</td>
<td>0.40</td>
</tr>
<tr>
<td>6</td>
<td>(14.7-16.6)</td>
<td>5</td>
<td>15.6</td>
<td>0.93</td>
</tr>
<tr>
<td>5</td>
<td>(12.6-15.2)</td>
<td>7</td>
<td>14.7</td>
<td>0.47</td>
</tr>
<tr>
<td>4</td>
<td>(12.0-14.2)</td>
<td>5</td>
<td>11.5</td>
<td>0.09</td>
</tr>
<tr>
<td>3</td>
<td>(11.4-13.4)</td>
<td>3</td>
<td>12.0</td>
<td>0.72</td>
</tr>
<tr>
<td>2</td>
<td>(10.7-12.3)</td>
<td>3</td>
<td>12.1</td>
<td>0.47</td>
</tr>
<tr>
<td>1-0</td>
<td>(10.5-11.7)</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Reference values are based on 11 participants per NRS score.

Values are mean and (95% CI)

Table 14.3: Results for postural sway velocity AP across three repeated measurements at 2-3 day intervals

<table>
<thead>
<tr>
<th>NRS score</th>
<th>Reference values</th>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>mVel ML</td>
<td>p-value</td>
</tr>
<tr>
<td>8</td>
<td>(16.8-20.0)</td>
<td>10</td>
<td>(15.4-19.6)</td>
<td>0.71</td>
</tr>
<tr>
<td>7</td>
<td>(14.7-16.9)</td>
<td>5</td>
<td>14.9</td>
<td>0.84</td>
</tr>
<tr>
<td>6</td>
<td>(12.2-13.7)</td>
<td>5</td>
<td>14.6</td>
<td>0.11</td>
</tr>
<tr>
<td>5</td>
<td>(11.3-14.4)</td>
<td>7</td>
<td>11.0</td>
<td>0.10</td>
</tr>
<tr>
<td>4</td>
<td>(10.1-12.4)</td>
<td>5</td>
<td>9.8</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>(10.1-12.2)</td>
<td>3</td>
<td>11.2</td>
<td>0.95</td>
</tr>
<tr>
<td>2</td>
<td>(9.0-10.6)</td>
<td>3</td>
<td>10.0</td>
<td>0.76</td>
</tr>
<tr>
<td>1-0</td>
<td>(8.5-9.5)</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Reference values are based on 11 participants per NRS score.

Values are mean and (95% CI)
Table 14.4: Results for 90% circle diameter across three repeated measurements at 2-3 day intervals

<table>
<thead>
<tr>
<th>NRS score (Reference values)</th>
<th>Session 1</th>
<th></th>
<th></th>
<th>Session 2</th>
<th></th>
<th></th>
<th>Session 3</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>mVel ML (p-value)</td>
<td>n</td>
<td>mVel ML (p-value)</td>
<td>n</td>
<td>mVel ML (p-value)</td>
<td>n</td>
<td>mVel ML (p-value)</td>
<td>n</td>
</tr>
<tr>
<td>8 (15.0-16.9)</td>
<td>10</td>
<td>15.1 (0.27)</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>7 (14.7-16.1)</td>
<td>5</td>
<td>16.4 (0.17)</td>
<td>3</td>
<td>14.7 (0.35)</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td></td>
</tr>
<tr>
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<td>5</td>
<td>15.4 (0.16)</td>
<td>4</td>
<td>16.2 (0.36)</td>
<td>2</td>
<td>13.9 (0.97)</td>
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<td></td>
<td></td>
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<tr>
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<td>12.3 (0.77)</td>
<td>5</td>
<td>12.3 (0.78)</td>
<td>2</td>
<td>14.8 (0.18)</td>
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<td></td>
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</tr>
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<td>11.4 (0.33)</td>
<td>5</td>
<td>13.7 (0.14)</td>
<td>5</td>
<td>11.6 (0.41)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3 (11.5-13.4)</td>
<td>3</td>
<td>13.3 (0.45)</td>
<td>14</td>
<td>11.0 (0.05)</td>
<td>10</td>
<td>12.6 (0.83)</td>
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<td></td>
</tr>
<tr>
<td>2 (11.5-13.1)</td>
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<td>5</td>
<td>11.4 (0.25)</td>
<td>13</td>
<td>11.6 (0.18)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-0 (11.1-12.2)</td>
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<td>-</td>
<td>2</td>
<td>12.2 (0.96)</td>
<td>6</td>
<td>11.1 (0.11)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reference values are based on 11 participants per NRS score.

Values are mean and (95% CI)

14.4. Discussion

This study aimed to investigate alterations in COP excursions associated with decreasing pain intensities. As an observational study with no control group or randomization of patients, it was neither intended nor designed to investigate any effect of manual therapies on non-specific low back pain. Therefore, no causality can be established.

While the reduction in pain followed a course of manual interventions, placebo, analgesic medication or natural history may have elicited similar results with regards to the associated sway alterations. The study design did not intend or allow to assess or quantify any potential additional biomechanical benefit of the therapeutic intervention on postural sway.
During the course of the three measurements, a dropout rate of 25% (13/51) occurred at session three while the groups at measurement 2 remained complete. As the data of these participants was completely removed from the study, no further statistical adjustment such as "intention-to-treat" analysis was deemed necessary. Although for a longitudinal observational study incomplete data sets are not necessarily excluded, their removal was deemed appropriate as individual results are followed over the course of the three sessions. The inclusion of incomplete sway data may adversely affect group means per measurement due to inter-subject variability and thereby alter the interpretation of the results.

Irrespective of the unclear underlying mechanism, the observed decrease in pain intensity over three measurements exceeded two points on an NRS score and is therefore considered clinically significant [297, 339, 340]. The study design did not set out to distinguish whether one treatment was associated with a more significant decrease in pain compared to others and therefore this cannot be commented on.

Previously, a linear relationship between COP sway and NRS scores in NSLBP and NSNP patients was demonstrated (Chapter 9 and 10). The trend observed in this study further strengthens the impression that this close association between COP excursions and pain intensity also exists if the original pain NRS-scores change. The flattening of the line that can be observed with the averaged postural sway measures at session 2 and 3 (Figures 14.3 and 14.4) may be at least partially associated with the results of the individual whose sway velocity increased from measurement 2 (11.6 mm/s mVel ML, 19.2 mVel AP) to measurement 3 (20.7 mm/s mVel ML, 21.3 mVel AP).

The pain reduction occurred following a series of non-specific therapeutic interventions. However, any contribution of this intervention, placebo effects or pain remission due to natural cause remains unclear. As a general trend, both group means and individual COP
measurements indicate that a decrease in postural sway was observed if NRS scores also decreased. If this was not the case, the COP excursions remained similar (Figures 14.5 and 14.6). However, as no patients experienced significant overall pain aggravation, the results do not permit to demonstrate that this in turn leads to increasing postural sway.

The observed relationship between pain intensity and COP excursions did not quite meet the results predicted by our previous regression analysis (Chapter 9.4.7). The equation suggested, for example, an increased by 1.53 mm/s in mVel ML for every NRS constituent score alteration. Taking Figure 14.7 as a basis, there was a decrease in pain perception of about 4 on the NRS scale between measurement 1 and 2. This would correspond to a predicted decrease in sway velocity of about 6.2 mm/s or, in more practical terms, of 55% in when taking the mVel ML of healthy controls as a reference (compare Chapter 9.4.7). However, the observed change only reached about 4.5 mm/s, a decrease of around 40%.

The results of our study warrant caution in interpretation. First of all, pain perception is multifactorial [341] and in addition to functional impairments, psychological aspects may play an important role. This was not assessed for and therefore no conclusions can be reached regarding their implications. It is further possible that both intra- and inter-subject variability in postural sway is masked when calculating means and therefore difficult to interpret.

In addition, the data shows quite wide variations in postural sway velocity likely due to the low sample sizes, particularly at medium pain intensities. When groups consisted of larger patient numbers, generally no significant sway differences were observed compared to other patients experiencing similar pain at baseline. The results from this study suggest that each group should consist of around 10 participants for further analyses. Considering a dropout rate of around 25%, about 14 participants should therefore be enrolled. However, with regards to assessing changes in sway or pain intensity at the follow up recordings, sample size
calculations are unable to take this into account as the number of patients that did or did not show alterations in the variable of interest cannot be predicted.

At first sight, these results are quite interesting as a larger inherent variability would have been expected. On the other hand, it is consistent with the subjective nature of pain perception. If a group of individuals receives an identical painful stimulus, a certain variation in pain perception will occur as a result [342]. However, this study suggests that similar postural sway responses occur in those patients reporting the same NRS-score. Secondly, the overlapping 95% CIs for all COP parameters observed between NRS scores particularly at lower NRS scores (Chapters 9 and 10) make results within the same range more probable.

Our results further suggest that the presence of pain may be responsible for alterations in postural sway [196] rather than changes/alterations in proprioceptive information caused by chronic damage to sensory tissues in the low back. Even considering neural plasticity, any reversal of such alterations appears unlikely within the 2-3 day period between measurements.

Further investigations with larger number of participants are needed to confirm the observed trend for all NRS-scores. However, an optimal sample size is difficult to determine as the number of patients per NRS score at follow-up recordings cannot be predicted. Also, studies employing analgesics are indicated to further assess the role of direct pain relief compared to the biomechanical, functional approach applied here. Another approach may be to assess sway pattern of those with natural remission without any intervention.
14.4.1. Clinical considerations

Although the results have to be interpreted with some caution, the COP measurement protocol used in this study may be suitable as an objective outcome measure for clinical monitoring purposes. This in turn also suggests that pain assessment by NRS-11 may be equally objective, thereby limiting the clinical use of COP measures for this specific purpose.

As previously described, it has been demonstrated that elderly fallers show significantly increased COP excursions compared to non-fallers [1, 343, 344]. There is also evidence that higher COP sway is associated with a higher risk of falling [102] and sustaining injuries as a consequence, although this is subject to debate [345, 346]. Consequently, if such individuals are additionally suffering from pain, this may further increase the risk of falling in addition to any age-related or pathological changes in postural stability. As this study shows lower COP excursions to be associated with decreasing pain intensities, this underlines the importance of pain control particularly in this population to reduce COP sway and increase postural stability.

14.4.2. Limitations

There are various limitations to this study. The issues associated with small sample sizes became even more pronounced by the fact that the number of patients per NRS score varied considerably as pain levels changed. Some NRS groups consisted of only n=2, as seen particularly at higher pain intensities as pain levels decreased over the course of the measurements. This rendered a meaningful statistical analysis difficult. On the other hand, other pain groups grew to n=14 as a result, which strengthened the conclusions drawn from these data.
In addition, the study design did not allow to determine whether decreasing pain scores alone was responsible for the decreasing postural sway or whether the manual intervention added an additional benefit by increasing biomechanical function. Based on the available literature, however, the latter appears unlikely to exhibit any significant effect (Chapter 5). Furthermore, the cut-off age of 50 years does not allow to extend the results to a geriatric population as the decreased pain perception in this age group [300] may not lead to similar postural responses. The same accounts for adolescents and children.

14.5. Conclusions

Irrespective of the subjective nature of pain perception and the unclear causative factors, the results of this study suggest that the close association between the COP parameters and perceived pain levels previously described is maintained if pain levels change. Although the results have to be interpreted with some caution, COP measurements may be suitable as an objective outcome measure for clinical monitoring purposes. However, these results in turn also suggest that pain assessment by NRS-11 may be equally objective, thereby potentially limiting the clinical use of COP measures for this specific purpose.
ON THE RELATIONSHIP BETWEEN ALTERED PAIN LEVELS ASSOCIATED WITH NON-SPECIFIC MANUAL INTERVENTIONS AND THE MAGNITUDE OF COP EXCURSIONS IN NSNP PATIENTS
CHAPTER 15

On the relationship between altered pain levels following non-specific manual interventions and the magnitude of COP excursions in NSNP patients

15.1. Background

In the previous chapter it was described that the linear relationship between COP excursions and NRS scores of NSLBP patients is maintained with changing pain levels, in this case following a series of manual therapeutic interventions.

This study will explore whether these observation can also be made in patients with NSNP using the same procedures.

15.2. Materials and methods

15.2.1. Participants

The participants included in this study were recruited from the previously enrolled group of 70 NSNP sufferers (see Chapter 10). They agreed to complete a course of three COP measurements and manual therapeutic interventions. Based on their availability and willingness to participate it was aimed to enrol around 40 participants for both symptomatic and an aged-matched control group.
15.2.2. Procedures

The procedures are identical to those described and applied in the previous chapter. The treatments were again administered by the same two experienced chiropractors (TB and AS) at 2-3 day intervals and targeted the whole kinematic chain.

15.2.3. Data analysis

To assess changes in postural sway velocity and NRS-scores, means, SDs and 95% CIs were calculated for all dependent variables. Independent samples t-test was performed to analyze differences between pain groups across the three measurements. The level of statistical significance was set at \( p \leq 0.05 \).

15.3. Results

15.3.1. Participants

Seventy patients with NSNP participated in the initial measurement to provide baseline data (Chapter 10). Of the 43 individuals that initially consented to participate in three measurements and receiving a series of manual interventions for this study, 32 individuals (84%) completed the full course. A matching number of controls (n=32) were selected randomly from the overall 77 healthy participants enrolled in the NSLBP study (Chapter 9).

Significant pain relief after less than three interventions (n=3) accounted for most of the loss to follow-up (n=4). Other reasons were the unwillingness to participate in the COP measurements while continuing treatments (n=2) while one patient was referred to medical
specialist for the suspicion of an occult disc prolapse. A comprehensive flowchart of procedures and participants is presented as Figure 15.1.

All healthy and symptomatic individuals were able to complete the measurements without difficulty. The characteristics of the participants are shown in Table 15.1.
Table 15.1: Patient characteristics

<table>
<thead>
<tr>
<th></th>
<th>NSNP intervention group (n=36)</th>
<th>Healthy controls (n=36)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>38.3±8.1</td>
<td>40.0±8.9</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176.9±8.8</td>
<td>175.6±6.3</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>75.3±11.6</td>
<td>74.6±10.3</td>
</tr>
<tr>
<td>BMI</td>
<td>23.8±2.9</td>
<td>24.7±4.0</td>
</tr>
<tr>
<td>NRS-11 score at baseline</td>
<td>5.0±1.8</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Values are mean ± SD

15.3.2. Pain intensity over the course of three therapeutic interventions

The pain intensity decreased from NRS 5.0±1.8 (95% CI 4.4-5.6) to 3.3±1.8 (95% CI 2.6-3.9) by measurement 3. Six patients (6/36, 17%) reported an increase in pain of 1 NRS level at one of the measuring appointments. However, the overall NRS scores either still decreased or remained at baseline level (Figure 15.2).
Figure 15.2: Development of individual and mean NRS-scores over three measurements

One grey line may indicate pain scores of several participants.

15.3.3. Relationship between pain intensity and postural sway

With few exceptions (3/36, 8%), all participants experienced lower associated postural sway velocities at measurement 3 compared to measurement 1 (Figure 15.3 and 15.4).
Figure 15.3: Individual changes in mVel ML and AP over three measurements (n=36)
With 13 NSNP patients (36%) the intervention did not result in a clinically significant pain reduction (≥2 NRS scores) and the NRS scores changed less than or equal to one score (Figure 15.5 and 15.6). With the overall pain intensity remaining nearly constant at about 4.8, a decrease in sway velocity of 1.1 mm/s was noted in ML while only a very small variance of 0.4 mm/s in AP direction occurred.
Figure 15.5: Pain intensity and mVel ML for participants with a change in NRS scores of ≤1 over the course of three measurements (n=13)

One grey line may indicate pain scores of several participants.
Figure 15.6: Pain intensity and mVel AP for participants with a change in NRS scores of ≤1 over the course of three measurements (n=13)

One grey line may indicate pain scores of several participants

One participant exhibited an increased sway velocity at measurement 3 compared to session 2 with decreasing pain intensities, while overall a decrease in mVel ML compared to baseline can be observed. Generally, the included NSLBP patients exhibited decreased mean velocities (12.8 mm/s at measurement 3 compared to 17.1 mm/s at baseline) as pain decreased from NRS scores 7.0 to about 2.5. This corresponds to a decrease in mVel of about 6% per NRS score (Figure 15.7).

300
**Figure 15.7:** Pain intensity and mVel ML for participants with a change in NRS scores of $\geq 4$ over the course of three measurements ($n=5$)

One grey line may indicate pain scores of several participants.

**Figure 15.8** demonstrates the changes associated with decreasing NRS-scores for mean sway velocity in AP direction, where the decrease in pain intensity of about 4.5 scores is associated with an average decrease in sway velocity of about 4.5 mm/s.
Figure 15.8: Pain intensity and mVel AP for participants with a change in NRS scores of ≥4 over the course of three measurements (n=5)

For all three COP parameters, the results indicate that with few exceptions there were no significant differences between either the results of the baseline measurement and the reference data or between postural sway at session 2 and 3 compared to the COP reference values.
No differences in mVel or 90% circle diameter was present when comparing those reporting a certain pain intensity at either baseline or follow up. When several patients were measured (n≤4), a significant difference compared to the reference values was only noted for mVel ML at measurement 2 (NRS score 4) and mVel AP at measurement 1 (NRS score 7).

**Table 15.2:** Results for postural sway velocity ML across three repeated measurements at 2-3 day intervals

<table>
<thead>
<tr>
<th>NRS score</th>
<th>Reference values</th>
<th>Measurement 1</th>
<th>Measurement 2</th>
<th>Measurement 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>mVel ML</td>
<td>p-value</td>
</tr>
<tr>
<td>8</td>
<td>20.0 (17.9-22.2)</td>
<td>4</td>
<td>22.3</td>
<td>0.33</td>
</tr>
<tr>
<td>7</td>
<td>19.1 (17.6-20.6)</td>
<td>4</td>
<td>19.8</td>
<td>0.69</td>
</tr>
<tr>
<td>6</td>
<td>17.0 (15.9-18.2)</td>
<td>7</td>
<td>16.1</td>
<td>0.30</td>
</tr>
<tr>
<td>5</td>
<td>13.7 (12.2-15.1)</td>
<td>6</td>
<td>13.4</td>
<td>0.28</td>
</tr>
<tr>
<td>4</td>
<td>11.8 (10.9-12.8)</td>
<td>7</td>
<td>11.4</td>
<td>0.59</td>
</tr>
<tr>
<td>3</td>
<td>11.7 (10.9-12.7)</td>
<td>5</td>
<td>11.5</td>
<td>0.67</td>
</tr>
<tr>
<td>2</td>
<td>10.5 (9.7-11.4)</td>
<td>3</td>
<td>9.4</td>
<td>0.18</td>
</tr>
<tr>
<td>1-0</td>
<td>11.2 (10.6-11.9)</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Reference values are based on 11 participants per NRS score.

Values are mean and (95% CI)
Table 15.3: Results for postural sway velocity AP across three repeated measurements at 2-3 day intervals

<table>
<thead>
<tr>
<th>NRS score</th>
<th>Reference values</th>
<th>Measurement 1</th>
<th>Measurement 2</th>
<th>Measurement 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>mVel ML</td>
<td>p-value</td>
</tr>
<tr>
<td>8</td>
<td>16.7 (14.6-18.9)</td>
<td>4</td>
<td>20.0</td>
<td>0.12</td>
</tr>
<tr>
<td>7</td>
<td>15.3 (13.6-17.0)</td>
<td>4</td>
<td>13.0</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>16.3 (14.6-18.1)</td>
<td>7</td>
<td>14.7</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>13.1 (11.8-14.5)</td>
<td>6</td>
<td>13.0</td>
<td>0.10</td>
</tr>
<tr>
<td>4</td>
<td>11.9 (10.4-13.2)</td>
<td>7</td>
<td>12.0</td>
<td>0.89</td>
</tr>
<tr>
<td>3</td>
<td>10.7 (9.5-12.0)</td>
<td>5</td>
<td>9.6</td>
<td>0.17</td>
</tr>
<tr>
<td>2</td>
<td>8.9 (8.2-9.6)</td>
<td>3</td>
<td>8.3</td>
<td>0.23</td>
</tr>
<tr>
<td>1-0</td>
<td>9.1 (8.5-9.5)</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Reference values are based on 11 participants per NRS score.
Values are mean and (95% CI)

Table 15.4: Results for 90% circle diameter across three repeated measurements at 2-3 day intervals

<table>
<thead>
<tr>
<th>NRS score</th>
<th>Reference values</th>
<th>Measurement 1</th>
<th>Measurement 2</th>
<th>Measurement 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>mVel ML</td>
<td>p-value</td>
</tr>
<tr>
<td>8</td>
<td>16.1 (14.7-17.5)</td>
<td>4</td>
<td>16.9</td>
<td>0.43</td>
</tr>
<tr>
<td>7</td>
<td>15.7 (14.9-16.5)</td>
<td>4</td>
<td>16.6</td>
<td>0.08</td>
</tr>
<tr>
<td>6</td>
<td>15.0 (13.9-16.1)</td>
<td>7</td>
<td>14.2</td>
<td>0.39</td>
</tr>
<tr>
<td>5</td>
<td>13.2 (12.3-14.1)</td>
<td>6</td>
<td>12.5</td>
<td>0.73</td>
</tr>
<tr>
<td>4</td>
<td>12.1 (11.6-13.3)</td>
<td>7</td>
<td>12.5</td>
<td>0.59</td>
</tr>
<tr>
<td>3</td>
<td>12.5 (11.6-13.3)</td>
<td>5</td>
<td>11.0</td>
<td>0.016</td>
</tr>
<tr>
<td>2</td>
<td>10.4 (9.8-11.0)</td>
<td>3</td>
<td>10.0</td>
<td>0.36</td>
</tr>
<tr>
<td>1-0</td>
<td>11.7 (11.1-12.2)</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Reference values are based on 11 participants per NRS score.
Values are mean and (95% CI)
15.4. Discussion

As with the previous study involving NSLBP patients, this study was not intended to investigate any effect of manual therapies on neck pain but to assess the effect of pain reduction on COP excursions.

Compared to the NSLBP study, the drop-out rate was lower at 19% (7/36) and the data of these patients was removed from the study. Therefore, no further statistical adjustment was deemed necessary.

In this NSNP group, less people showed a decrease of more than or equal to 4 NRS scores compared to the NSLBP study with 13/36 (14%) and 9/38 (24%), respectively. Also, a larger number remained on fairly constant pain levels (13/38, 34% compared to 7/36, 19%). This may be due to the generally lower baseline pain scores, leaving both less room for improvement and also increasing the variability of pain scoring observed at medium intensities (see Chapters 9 and 10).

The potential underlying mechanisms behind the altered sway pattern in association with decreasing pain intensities remains the same as described in the previous chapter. This discussion will therefore focus on the differences in the postural response to altering pain intensities between NSLBP and NSNP patients. However, the fact that similar results could be demonstrated with a total of 74 individuals with neck and low-back pain further strengthens the conclusions regarding pain interference as the causative factor.

Generally, the results of the NSLBP and NSNP studies were very similar. The linear trend between NRS scores and the COP parameters is maintained with altering pain intensities. This can be concluded from the fact that the COP measures associated with altered NRS
scores at measurements 2 and 3 generally show no difference to sway data collected from individuals experiencing identical pain levels at baseline.

In ML direction, mVel decreased by about 10% over the course of three measurements (when taking healthy controls as a reference) despite no change in average pain intensity (Figure 15.5). No ready explanation can be found for this. However, previously a 5-10% higher percentage of sway in ML direction was observed at NRS-scores 4 to 5 (Chapter 10.4.5), probably leading to an increased margin for inter-subject variability. A learning effect appears unlikely as there was only a minimal corresponding change in mVel AP of less than 4%.

As with NSLBP sufferers, the observed postural sway data did not quite confirm the results predicted by our previous regression analysis (Chapter 10.4.4). The regression equation suggested an increased by 1.2 mm/s in mVel ML and 1.67 mm/s for every NRS constituent score alteration. Between measurements 1 and 3, there was an overall decrease in pain intensity of about 4.5 NRS scores (Figure 15.8). This would correspond to a decrease in sway velocity of about 5.4 mm/s in ML and 7.5 mm/s in AP direction. However, the observed change remained at about 4.3 mm/s and 4.5mm/s, respectively. This difference may be explained by the fact that due to the number of variables that may affect the COP parameters, regression equations give only estimates and are therefore unlikely to predict the real values.

Again, the study design did not allow to determine with confidence whether decreasing pain scores alone were causative for the altered postural sway pattern or whether the manual interventions added an additional biomechanical benefit. It appears likely, however, that decreasing pain due to whatever cause, including natural remission, may lead to similar results. So far there is no evidence for the effectiveness of manual interventions on postural sway or any additional benefit compared to other modalities. Any sway alterations appear to be associated with pain reduction itself rather than the modality that caused it.
15.4.1. Limitations

Limitations of this study once more include the limited age range and the small sample size. However, as discussed before, the combined number of patients of both the NSLBP and NSNP study nearly doubles the overall participants to n=74. As the results were very similar, this strengthens the conclusions regarding the fact that the relationship between sway and pain intensity is maintained if pain levels change.

15.5. Conclusions

This study further underlines the close linear correlation between COP sway and the pain intensity, even if NRS scores are altered. Although the results have to be interpreted with similar caution as our previous study on NSLBP patients, the COP measurement protocol appears sensible to detect changes in COP excursions associated with changing pain intensities and therefore suitable as an objective outcome measure for clinical monitoring purposes.
ADVERSE EFFECTS ASSOCIATED WITH CONDUCTING COP MEASUREMENTS AND THE ADMINISTRATION OF MULTIMODAL THERAPEUTIC INTERVENTIONS
CHAPTER 16

Adverse effects associated with conducting COP measurements and the administration of multimodal therapeutic interventions

16.1. Background

Depending on the physical examination findings, it is common to find that physical treatments may have targeted the whole kinematic chain irrespective of the symptomatic area (Chapter 6.4.9).

Systematic studies indicate that minor symptoms after spinal manipulation are commonly reported by patients [347] with an incidence rate of around 50% [347, 348]. More serious complications attributed to cervical manipulation [349, 350], misdiagnosis [351], presence of a herniated disc, or improper technique selection [352] are very rare events.

Soft tissue techniques, such as massage, are extremely rare and are usually caused by rather unusual and extremely vigorous technique [353, 354]. In contrast, muscular reactions occur more frequently occurring in about 10% of patients [355]. There are no reports yet on possible adverse effects of Active Release Technique [271] or Post-Isometric Release [270], however, a comparable incidence rate may be expected due to the similar nature of procedures.

With regards to the force platform measures, there are no adverse incidence reports available in the literature.
In this chapter any adverse effects associated with a) the forceplate measurements and b) the therapeutic interventions will be investigated in order to document the occurrence of these events during this thesis.

16.2. Methods

16.2.1. Data collection

COP measurement procedures
All participants were carefully observed during the measurements as outlined in Chapter 6. Any incidences such as falls, psychological distress or injuries sustained during procedures associated with obtaining COP data were to be recorded. In addition, the situation leading to the incidence was to be recorded and described in detail.

Therapeutic interventions
During the conduct of the experiments, the occurrence of any adverse reactions were recorded in the patient files and extracted after completion of the COP recordings. Patients were routinely asked each visits about adverse effects and, if present, the location and type of those reactions were recorded (e.g. muscle ache, worsening of symptoms). Questions further included the time of onset (same day/later) as well as a rating of the perceived severity (mild/moderate/severe). With regards to the intensity, there was no cut-off level for inclusion as adverse reaction. Instead, all forms of discomfort (even mild muscle aches) were counted.

16.2.2. Data analysis

COP measurement procedures
Adverse effects were categorized for type, circumstances that lead to the incident and severity. Simple descriptive statistics were to be used.
Therapeutic interventions

Positive responses with regards to adverse effects were categorized for type, time of onset and severity. Simple descriptive statistics were applied to calculate percentages.

16.3. Results

16.3.1. Force platform measurements

With an overall 1767 recordings being completed throughout this dissertation, there were no incidents or adverse reactions associated with the conduct of the COP measures. This confirms the preliminary results from the feasibility pilot study where it was concluded that the experimental setup was perceived as safe (Chapter 7.2).

16.3.2. Therapeutic intervention

A total of 386 multimodal physical treatments as defined in Chapter 6.4.2. were administered. Due to conflicting time schedules, not all interventions could be followed up by a COP measurement.

About 46% reported minor or moderate muscle ache or soreness, however there was one case of intensive muscle ache and this was the only adverse incident graded as severe (Table 17.1). Overall, the majority of adverse events were of mild (137/175, 78%) or moderate (37/175, 21%) intensity and mostly consisted of muscle pain (122/175, 70%). Only rarely a worsening of the original symptoms were reported (29/175, 17%).
Table 16.1: Adverse reactions associated with the multimodal therapeutic intervention

<table>
<thead>
<tr>
<th>Type of adverse effect</th>
<th>Time of onset</th>
<th></th>
<th>Intensity of adverse effects</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Same day</td>
<td>Later</td>
<td>Mild</td>
</tr>
<tr>
<td>Worsening of original symptoms</td>
<td>13 (7)</td>
<td>16 (9)</td>
<td>26 (15)</td>
<td>3 (2)</td>
</tr>
<tr>
<td>Ache in muscles</td>
<td>76 (43)</td>
<td>47 (27)</td>
<td>90 (51)</td>
<td>32 (18)</td>
</tr>
<tr>
<td>Headache</td>
<td>12 (7)</td>
<td>7 (4)</td>
<td>17 (10)</td>
<td>2 (1)</td>
</tr>
<tr>
<td>Other</td>
<td>3 (2)</td>
<td>1 (0.6)</td>
<td>4 (2)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>

Values are total number (%)

16.4. Discussion

The absence of any incidences associated with the measurements can be explained by the simplicity of the postural task in addition to clear instructions and the safety handles attached to the forceplate. As outlined in Chapter 7.2, the feeling of safety perceived by the participants may have allowed them to concentrate and focus on the experimental procedures.

The participants found the presence of the safety handles reassuring, and very few did not grab hold of it at some point between trials when stepping on and off the platform. Although none of them was in real need to regain balance and prevent a fall, safety handles are nevertheless recommended for future studies. This may particularly useful for those enrolling balance impaired geriatric participants.

The overall adverse effect rate of 46% is very close to the 50% reported in the literature [347, 348]. Due to the diversity of the manual interventions, the nature and number of adverse effects related to a particular form of treatment remains unclear because the study design did not allow to identify relative associations. In addition, it was a limitation that the recording of these adverse events was done by a chiropractor within the clinic. This may have inhibited the participants declaring such an event.
16.5. Conclusions

No adverse effects occurred during or as a result of the COP measurements. Those associated with the therapeutic intervention were mostly of mild intensity and the overall rate remained within the expected range. The experimental protocol applied in these studies may be used with confidence in patients as well as healthy controls.
DISCUSSION AND CONCLUSIONS
CHAPTER 17

Discussion and conclusions

17.1. Introduction

The broad aim of this thesis was to study postural sway and its relationship to spinal pain and disability. For this purpose, literature reviews and experiments using COP measures were used which established that there was indeed such a relationship. This relationship may have important clinical utility.

As a discussion concluded each chapter, these sections will not be restated in detail. Before concluding on the issues and possibilities arising from the results reported in this thesis, some basic aspects regarding data acquisition should be noted.

17.2. Aspects of data acquisition

When reading a study, judging the quality of the measuring equipment is not usually possible due to the vast number of different systems in usage. It is, for example, possible that a system is highly reliable but the data collected is not valid e.g. due to errors in the calculations underlying the COP parameters. Other systems again may be valid but suffer from calibration errors.

Adding these factors to the broad range of COP parameters developed in recent years, the variability in participant characteristics and the issue of reliability associated with the experimental protocol, it underlines potentially why there is rarely inter-study agreement on
postural sway results. This has been a hallmark of COP related studies so far and it is unlikely to change without a generally agreed form of standardization.

It remains unclear why so far there is no such generally agreed standardization of measurement procedures as several studies have established basic guidelines for reliable experimental setups (Chapter 2). The diversity of possible postural tasks (e.g. bipedal or one-legged stance) depending on participant characteristics and research aims may be the most prominent reason.

By identifying and testing a best practice experimental setup as a basis for the subsequent experiments, most of the limiting factors previously described have been avoided in this doctoral project and the reported results may be used with confidence. The reliability pilot study further showed that obtaining reliable data and identifying trial frequency and sampling durations suiting the individual research purpose is achievable. Therefore, conducting such procedures and presenting the data should be part of the results section of COP related studies. It is hoped that the systematic review regarding this topic (Chapter 2) will aid in this process.

The COP parameter reliability data also shows that the sampling duration could have been reduced by about half a minute per trial or the number of trials limited to two while still obtaining excellent reliability values. Saving a total of 90sec constitutes a 33% decrease in physical demand which may facilitate the compliance of symptomatic participants in particular. However, it should be noted that the reference values permitting these conclusions originated from a small number of healthy individuals. So, given the unforeseen possible implications associated with pain perception, it was decided to follow the experimental protocol supported by the previous literature review (Chapter 2).
In hindsight, it turned out that these longer sampling durations probably offered a more realistic insight into sway alterations in pain patients. This was signified by the fact that the non-recorded 5 seconds period selected to compensate for initial postural adaptation proved to be insufficient as shown by the decreasing mVel ML with longer durations (Table 7.1.2). This trend reached a plateau at about 2-3 repetitions of 90sec duration. Although this data was collected in healthy individuals, pain sufferers with impaired postural stability may require at least the same amount of time. Therefore, averaging three 90sec recordings offers data that remains unaffected by potentially highly variable COP excursions during initial adaptation periods.

17.3. Pain and postural sway

A linear relationship between pain and postural sway was identified that may potentially be used as a clinical monitoring tool during treatment and rehabilitation. Compared to pain assessment, which can be influenced by psychological states such as depression or mood changes, sway measures may prove to be a more objective choice. On the other hand, the simplicity and generally accepted validity of pain scoring may give these instruments preference in everyday clinical practice.

The prospective studies further showed that the linear relationship between pain and postural sway is maintained with altering pain levels. As this project was not designed to investigate the mechanisms underlying increased postural sway in pain sufferers, any conclusions on this topic warrant some caution. Nevertheless, the results may contribute to the ongoing discussion.
An imprecise estimation of the center of mass position due to deterioration of proprioceptive information associated with chronic damage of sensory tissues has been proposed as a possible reason for increased COP excursions in pain sufferers [163, 164]. However, considering the long previous pain duration of the enrolled patients (16.6±23.3 to 24.8±40.0 weeks), any reversal of such neuro-physiological impairments appears unlikely to happen within the short period of the measurement series. The observed reduced postural sway with decreasing pain intensities at 3-4 day follow-up measurements is therefore not explained. Secondly, as the three painful regions showed very similar postural responses to pain, the proposed proprioceptive impairment appears less likely. Otherwise the NSNP patients would probably be expected to show greater COP excursions due to the high proprioceptive density in the neck [356].

The pain interference mechanism proposed by Crombez et al. [165] may offer a better explanation why decreasing pain levels were associated with reduced COP excursions in the short term. Here, discharge from high-threshold nociceptive afferents interferes with spinal motor-pathways [166] causing an increased pre-synaptic inhibition of muscle afferents [167] as well as affecting the central modulation of proprioceptive spindles of muscles [168]. If these alterations lead to decreased muscle control and the observed increased postural sway, it appears plausible that pain reduction may decrease this effect.

When Hodges proposed a new theory of adaptations of the motor system due to pain that involves both increased and decreased muscle activity [289], this opposes the idea of such a uniform pain inhibition [165]. However, the results behind arguing against pain interference as the causative factor for altered motor function originated from EMG based experiments involving muscles of the trunk during active movements [196]. Such muscles play no significant role in simple bipedal static task conditions that primarily involve ankle strategy [71].
While no final conclusions regarding the mechanisms behind increased postural sway in pain sufferers can be drawn at this point, inhibitory effects on muscle function induced and maintained by pain perception appears likely.

17.4. Applying the results in research and clinical practice

The sway results of the healthy individuals (n=77) may serve as reference data for researchers that employ an identical experimental protocol but prefer not to enroll their own control groups e.g. due to time or financial restraints. However, these values are only valid when measuring "normal, average" individuals. Caution may be warranted depending on the characteristics of the participants they are intended to be compared to - even if age and gender distributions are similar.

Sway data not collected as part of this doctoral project (and therefore not included) were obtained from 20 healthy elite ice hockey players and showed marked variability with sway velocities and sway area ranging between 50% and 200% of the COP reference values presented in Chapter 9. This finding of increased variability in postural sway is in general agreement with a previous small study of ice hockey players [357]. It may be attributed to different development of dynamic and static balance, an observation also described in ballet dancers [358]. It was proposed that athletes develop motor abilities for their sport specific balance tasks that are not (fully) transferable to postural control in daily life situations such as quiet standing [359], causing greater variability of COP excursions. Consequently, attempts to establish comprehensive reference values for such cohorts of professional athletes may be impractical due to their high inter-subject variability.
It further needs to be remembered that while COP recordings are commonly applied and generally accepted indirect measures of postural stability, their relevance and descriptive value remains ambiguous. It is, for example, unclear whether greatly increased or decreased sway in mid-aged healthy individuals compared to a control group is of any significance at all. No conclusion can be drawn from the results presented here. The resulting question therefore remains whether there is a broader practical value of routine COP measures in symptomatic spinal pain patients or those with a history of neurological or vestibular impairments (e.g. whiplash).

If, for example, an increased postural sway was to be taken as a rationale for implementing balance training, how are potentially decreasing COP excursions at follow-up to be interpreted? Can such changes be attributed to neurological recovery and thereby a real improvement of postural stability or is it rather a simple learning effect due to constant repetitions of a specific task such as wobble board exercises? In case of the latter, such "improvements" may not be transferable to everyday postural demands and monitoring postural sway would thereby prove to be of little or no value at all.

Furthermore, all results presented as part of this thesis only apply to the specific experimental setup used. Other studies employing different postural tasks such as one leg standing or compliant surfaces may not agree on the pain induced sway alterations described here or, in contrast, find them to be even more pronounced.

As discussed in the introduction, postural control is a multifactorial process which may explain why the regression equations presented in this thesis offered barely acceptable fits. Other factors that may (adversely) influence balance performance in both healthy and symptomatic individuals such as excitation, painless physical impairments, lack of focus or motivation, exertion due to previous activities or subtle vestibular or neurological impairments may often
go unnoticed during physical examination. As the inclusion and exclusion criteria in a research setting are further based on recollection of the participants in interviews or questionnaires, relevant previous injuries or illnesses may not be reported. In addition, age related changes may have an earlier onset than described in the literature (<50yrs). All those factors may influence COP data collection and cannot be adjusted for. In this respect, the limitations associated with small sample sizes may become even more apparent and should be kept in mind when interpreting postural sway results. This also contributes to the probably unavoidable inter-study variability of results.

17.5. Prospects for future studies

The results from this thesis offer interesting starting points for future research. Such studies may want to repeat the experiments presented here with additional parameters based on frequency or amplitude as those may offer further interesting additional information on postural sway behavior.

As there was no intention to establish any causality between the manual therapeutic interventions and pain alterations in this thesis, the next logical step would be to a) repeat the prospective trials with a control group receiving placebo treatment and b) investigate what trends can be observed when employing analgesic medication or simply observing natural remission.

To further explore this topic, future studies may want to monitor postural sway and pain levels at short intervals (e.g. hourly) to evaluate if the observed sway alterations occur simultaneously or whether changes in COP excursions precede or follow pain alterations. This may also contribute to answering the question regarding the underlying mechanisms. Results
from EMG recordings found that the removal of the painful stimulus did not lead to immediate cessation of pain related motor adaptations, but resulted in gradual normalization of postural responses [196]. In this case, however, multiple COP recordings may prove impractical and the fatigue or boredom effects previously ruled out for this setup may begin to manifest.

Furthermore, it would be interesting to measure COP excursions of patients with pathologies such as Parkinsonism, peripheral neuropathy or post-stroke disability with an identical experimental setup to assess and quantify differences and similarities between sway patterns. This may offer interesting insights into postural adaptations and motor strategies for balance control of such neurological cases compared to those of non-specific spinal pain sufferers and healthy controls.

Proprioceptive training has become a commonly employed aspect of physical rehabilitation. It remains unknown whether such training affects the magnitude COP excursions independent of any pain alterations. If this is the case, the clinical application of COP measures as an objective outcome measure may be limited for those patients as simple learning effects cannot be excluded.

The results analyzed and presented in this thesis are only a part of the data that have been collected from the enrolled participants, particularly with regards to the physical examinations. Further analyses of not presented data may for example look into possible associations between the magnitude of unequal weight bearing and the direction of COP excursions. In addition, it may be interesting to investigate whether these findings correlate with the side of sacro-iliac (SI) joint or lower extremity involvement. Apart from the physical examinations, this may involve analgesic blocks to identify whether and which of the SI joints is a source of pain.
17.6. Conclusions

Systematic literature reviews contained in this thesis described an increased postural sway in pain sufferers and helped to identify a best practice experimental procedures for COP measures.

Pilot studies confirmed the excellent reliability of this setup for both healthy and symptomatic groups. No effects of learning or fatigue were found. When the COP excursions of patients with non-specific spinal pain were compared to those of healthy individuals, a greater postural sway was observed in symptomatic individuals.

A major finding of this thesis was a linear relationship between the pain intensity and the parameters for all painful regions, while other variables such as age, gender, height, weight and BMI did not exhibit a significant effect on postural sway. This close relationship was maintained with altering pain levels. In addition, a similar linear relationship between pain intensity, the sway parameters and the disability ratings was identified.

Reduced postural sway with decreasing pain scores over a period of few days further indicates that pain interference rather than neuro-physiological adaptations may be the primary causative factor for pain related sway alterations.

The findings of this thesis suggest future clinical applications for COP measures as an objective outcome measure during rehabilitation and treatment. It also stresses the importance of initial pain regulation.

However, in order to allow for inter-study comparison of results, there is a strong need for a standardization of COP measurement procedures.
Monday, 19 April 2010

Dr Bruce Walker
School of Chiropractic and Sports Science
Murdoch University

Dear Bruce,

**Project No.** 2010/066
**Project Title** The clinical application of balance measure known as Centre of Pressure

Thank you for addressing the conditions placed on the above application to the Murdoch University Human Research Ethics Committee. On behalf of the Committee, I am pleased to advise the application now has:

OUTRIGHT APPROVAL.

Approvals are granted for three years. You will need to submit an annual report to the Research Ethics Office. Please note you are required to report immediately any unforeseen or adverse events especially if they might affect the ethical standing of the project. Once the project has been completed, please submit a Project Closure Report. All forms are available on the Research Ethics web-site.

I wish you every success for your research.

Please quote your ethics project number in all correspondence.

Kind Regards,

Dr. Erich von Dietze
Manager of Research Ethics

cc: Dr Rene Fejer
Alexander Ralph Ruhe

HREC Outright Approval Letter 080310

CRICOS Provider Code: 001253
ABN 61 616 369 313
Friday, 27 August 2010

Dr Bruce Walker
School of Chiropractic and Sports Science
Murdoch University

Dear Bruce,

Project No. 2010/066
Project Title The clinical application of balance measure known as Centre of Pressure

AMENDMENT: Increase number of participants from n=40 to n=70

Your application for an amendment to the above project, received on 27/08/2010 was reviewed by the Murdoch University Research Ethics Office and was;

APPROVED

As a condition of the approval of your human research ethics application you are required to report immediately anything, which might affect ethical acceptance of your project’s protocols, including:

- Adverse events
- Proposed changes in the protocols
- Unforeseen events that might affect continued ethical acceptability of the project.

Please quote your ethics permit number in all correspondence.

Kind Regards,

E. van Dette

Dr. Erich von Dette
Manager of Research Ethics

cc: Dr Rene Fejer; Alexander Ralph Ruhe
Appendix 2: Ethics Approval - Prospective Study

Research Ethics Office
Division of Research and Development

Chancellery Building
South Street
MURDOCH WA 6150
Telephone: 9360 6677
Facsimile: 9360 6686
human.ethics@murdoch.edu.au
www.research.murdoch.edu.au/ethics

Wednesday, 15 September 2010

Dr Bruce Walker
School of Chiropractic and Sports Science
Murdoch University

Dear Bruce,

Project No. 2010/173
Project Title The clinical application of Center of Pressure

Thank you for addressing the conditions placed on the above application to the Murdoch University Human Research Ethics Committee. On behalf of the Committee, I am pleased to advise the application now has:

OUTRIGHT APPROVAL

Approval is granted on the understanding that research will be conducted according the standards of the National Statement on Ethical Conduct in Human Research (2007), the Australian Code for the Responsible Conduct of Research (2007) and Murdoch University policies at all times. You must also abide by the Human Research Ethics Committee’s standard conditions of approval (see attached). All reporting forms are available on the Research Ethics web-site.

I wish you every success for your research.

Please quote your ethics project number in all correspondence.

Kind Regards,

[Signature]

Dr. Erich von Dietze
Manager of Research Ethics

cc: Dr Rene Fejer
Alexander Ruhe

HREC Outright Approval Letter 080110

CRICOS Provider Code: 001253
ABN 61 616 369 313

327
Appendix 3: Information letter for prospective healthy participants in prospective and pilot studies

Information Letter

Thank you for your interest in participating in this research project

“The clinical application of Center of Pressure”

This research is part of a doctorate program of Alexander Ruhe (MChiro) and has been approved by Human Research Ethics Committee and also the School of Chiropractic and Sports Science at Murdoch University in Perth, Western Australia, Australia.

Before you are asked for your consent, we would like to give you some more information to allow you to make an informed decision regarding your participation. If you require further information during the course of the trial, you may contact the clinic by phone or email. Your questions will be addressed by one of the chiropractors involved.

It is hoped that the research will not only contribute to the basic understanding of changes to postural stability (balance) under healthy and illness conditions, but also allow the early detection of balance problems and thereby aid in fall and injury prevention.

The research aims to assess postural balance by measuring the sway of the body in a standing position. This is done by tracking the movements of the Centre of Pressure (COP), which is the point at which the pressure of the body over the soles of the feet would be if it were concentrated in one spot. You will be asked to stand still on a broad measuring platform while your body sway is recorded.

You will also be asked to fill out a questionnaire regarding your present health status. You can refuse to disclose any elements of the information requested. During the recordings you will have to stand on the platform with your eyes closed five times for a duration of 90 seconds each. The time investment will be approximately 30 minutes. In the eyes closed situation you will be wearing a soft blindfold.

All care will be taken to ensure your on-site safety, however in the unlikely event of losing balance while standing on the measuring device we will be there to support you. In very rare instances you may fall and hurt yourself. In addition, standing blindfolded may provoke fear in a minority of people. In this case you may stop at any time.

All data collected from you will be treated confidentially. You will be allocated an individual ID number that prevents the allocation of data to your name as the trial continues. Only the researchers and chiropractors directly involved in the research will have access to the recordings or any personal data related to this research and no publication will identify you personally.
All information provided and data collected is treated as confidential and will not be released by the researcher to any third party unless required to do so by law.

Participation in the research is voluntary. You also may change your mind and withdraw from the trial at any stage and without any consequence.

No commercial or non-commercial sponsors are involved in the research and there are no financial benefits for any of the investigators. There are also no financial reimbursements or remuneration for the trial participants.

The research will be conducted in accordance with the National Statement on Ethical Conduct in Research involving Humans (Australia), the Murdoch University Guidelines and Codes of Practice for the Conduct of Research as well as the World Medical Association Declaration of Helsinki on Ethical Principles for Medical Research Involving Human Subjects.

Should you, for any reason regarding this research, want to file a complaint you may do so by contacting the Research Ethics Office at Murdoch University. Your complaint may be written in German language. The contact details are:

Research Ethics Office
Division of Research and Development
Chancellery Building
South Street
MURDOCH WA 6150

Phone:0061-8-93606677
Ask for Dr Erich von Dietze or by email to

Dr. Erich von Dietze
E.vonDietze@murdoch.edu.au

Or to the Ethics office:
human.ethics@murdoch.edu.au

If you wish to assist in this important research, please contact the clinic:

Praxis fuer Chiropraktik Wolfsburg
Porschestraße 1
38440 Wolfsburg

phone: 05361- 8481358
fax: 05361 - 8481378
www.chiropraktik-wolfsburg.de
info@chiropraktik-wolfsburg.de

Thank you for taking your time to read this information, if you have any further questions, please do not hesitate to ask any of the investigators.

This study has been approved by the Murdoch University Human Research Ethics Committee (Approval 2010/066). If you have any reservation or complaint about the ethical conduct of this research, and wish to talk with an independent person, you may contact Murdoch University's Research Ethics Office (Tel. 0061-8-9360 6677) or e-mail ethics@murdoch.edu.au). Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.
Appendix 4: Information letter for potential participants in the feasibility pilot study

Information Letter

Thank you for your interest in participating in this research project “The clinical application of Center of Pressure”.

This research is part of a doctorate program of Alexander Ruhe (MChiro) and has been approved by Human Research Ethics Committee and also the School of Chiropractic and Sports Science at Murdoch University in Perth, Western Australia, Australia.

Before you are asked for your consent, we would like to give you some more information to allow you to make an informed decision regarding your participation. If you require further information during the course of the trial, you may contact the clinic by phone or email. Your questions will be addressed by one of the chiropractors involved.

It is hoped that the research will not only contribute to the basic understanding of changes to postural stability (balance) under healthy and illness conditions, but also allow the early detection of balance problems and thereby aid in fall and injury prevention.

The research aims to assess postural balance by measuring the sway of the body in a standing position. This is done by tracking the movements of the Centre of Pressure (COP), which is the point at which the pressure of the body over the soles of the feet would be if it were concentrated in one spot. You will be asked to stand still on a broad measuring platform while your body sway is recorded.

You will also be asked to fill out a questionnaire regarding your present health status. You can refuse to disclose any information requested. During the recordings you will have to stand on the platform three times for a duration of 90sec each with your eyes closed.

The time investment will be 45-60min for the first session and 20-30min for the two follow-up measurements. While you are requested to participate in the follow-up sessions that will be arranged around your normal appointments in clinic, you may withdraw from the study at any time.

All care will be taken to ensure your on-site safety, however in the unlikely event of losing balance while standing on the measuring device we will be there to support you. In very rare instances you may fall and hurt yourself. In addition, standing blindfolded may provoke fear in a minority of people. In this case you may stop at any time.

All data collected from you will be treated confidentially. You will be allocated an individual ID number that prevents the allocation of data to your name as the trial continues. Only the researchers and chiropractors directly involved in the research will have access to the recordings or any personal data related to this research.
All information provided and data collected is treated as confidential and will not be released by the researcher to any third party unless required to do so by law.

Participation in the research is voluntary. Should you choose not to participate, you may remain a patient of the clinic as before and there will be no consequences. You also may change your mind and withdraw from the trial at any stage and without any consequence.

No commercial or non-commercial sponsors are involved in the research and there are no financial benefits for any of the investigators. There are also no financial reimbursements or remuneration for the trial participants.

The research will be conducted in accordance with the National Statement on Ethical Conduct in Research involving Humans (Australia), the Murdoch University Guidelines and Codes of Practice for the Conduct of Research as well as the World Medical Association Declaration of Helsinki on Ethical Principles for Medical Research Involving Human Subjects.

Should you, for any reason regarding this research, want to file a complaint you may do so by contacting the Research Ethics Office at Murdoch University. Your complaint may be written German language. The contact details are

Research Ethics Office
Division of Research and Development
Chancellery Building
South Street
MURDOCH WA 6150

Phone: 0061-8-9360 6677
Dr. Erich von Dietze
E.vonDietze@murdoch.edu.au

Or to the Ethics office:
human.ethics@murdoch.edu.au

If you wish to assist in this important research, please contact the clinic:

Praxis fuer Chiropraktik Wolfsburg
Porschestraße 1
38440 Wolfsburg

phone: 05361 - 8481358
fax: 05361 - 8481378
www.chiropraktik-wolfsburg.de
info@chiropraktik-wolfsburg.de

If you wish to participate, you may progress to signing the attached consent form.

This study has been approved by the Murdoch University Human Research Ethics Committee (Approval 2010/066). If you have any reservation or complaint about the ethical conduct of this research, and wish to talk with an independent person, you may contact Murdoch University's Research Ethics Office (Tel. 0061-8-9360 6677) or e-mail ethics@murdoch.edu.au). Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.
Appendix 5: Consent form for all participants of the pilot and prospective studies

**Einverständniserklärung**

Ich habe den Inhalt des Informationsbriefes bezüglich der Forschungsstudie “Die klinische Anwendung des Kraftangriffspunktes” vollständig gelesen und verstanden.

1. Ich nehme freiwillig an dieser Studie teil.


4. Meine Identität wird in keiner aus dieser Studie resultierenden Veröffentlichung preisgegeben.

5. Mein Name und Identität wird von den Messdaten separat aufbewahrt und ist nur für die Forscher zugänglich. Alle Daten werden anonymisiert unter Verwendung einer Identifikationsnummer ausgewertet.

6. Alle erteilten Informationen und gesammelten Daten werden als vertraulich behandelt und werden nicht an Dritte weitergeleitet, solange keine gesetzliche Verpflichtung dazu entsteht.

Name (in Druckbuchstaben): __________________________________________________

Unterschrift des Teilnehmers: _______________________________ Date:  …..../..…../…….

Unterschrift des Chiropraktors: ______________________________ Date: ..…../…..../…….

Ich möchte nach Beendigung der Studie über die Ergebnisse informiert werden  [ ] (bitte ankreuzen)

Diese Studie wurde von der Ethik-Kommission der Murdoch University genehmigt (Erlaubnis 2010/066). Sollten Sie irgendwelche Bedenken oder Beschwerden in Bezug auf die ethische Durchführung dieser Studie haben und möchten diesbezüglich Kontakt zu einer unabhängigen Person aufnehmen, können Sie das Büro für Forschungsethik der Murdoch University (Tel. 0061-8-9360 6677 oder email: ethics@murdoch.edu.au) kontaktieren. Alle Belange werden vertraulich behandelt und gründlich geprüft. Sie werden über den Ausgang der Untersuchung informiert.
### Appendix 6: Examination Sheet

#### Initial Examination

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<thead>
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<th>ID NO.:</th>
<th>EXAMINER:</th>
<th>DATE: / /</th>
</tr>
</thead>
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**AGE:**

**GENDER:**
- [ ] male
- [ ] female

**WEIGHT (kg):**

**HEIGHT (cm):**

**BMI:**

**Lumbar Spine and Pelvis**

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**Gillet's Test**

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<td>Restriction</td>
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<tr>
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<tr>
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**Gaenslen's Test**

<table>
<thead>
<tr>
<th>POSITIVE</th>
<th>NEGATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>Restriction</td>
</tr>
<tr>
<td>L</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

**Patrick's Faber Test**

<table>
<thead>
<tr>
<th>POSITIVE</th>
<th>NEGATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>Restriction</td>
</tr>
<tr>
<td>L</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

**Cervical Spine**

**Spurling's Test**

<table>
<thead>
<tr>
<th>POSITIVE</th>
<th>NEGATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>Radiation</td>
</tr>
<tr>
<td>L</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

**Distraction**

<table>
<thead>
<tr>
<th>AGGRAVATED</th>
<th>EASED</th>
<th>NO CHANGE</th>
</tr>
</thead>
</table>

**Nerve Tension Test**

<table>
<thead>
<tr>
<th>POSITIVE</th>
<th>NEGATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>Radiation</td>
</tr>
<tr>
<td>L</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

#### Static Palpation

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>Painful L</th>
<th>Painful R</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0-C1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2-C3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4-C5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C6-C7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7-T1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1-T2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2-T3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3-T4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4-T5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5-T6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6-T7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T7-T8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T8-T9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T9-T10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T10-T11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T11-T12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T12-L1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1-L2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2-L3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3-L4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4-L5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L5-L6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Reflexes (Grade 4, 3, 2, 1, 0)

- **BIC**
- **SRA**
- **PAT**
- **ACH**
- **PL**
- **HAM**
- **TRI**

#### Myotomal Strength (Grade 5, 4.3, 2.1, 0)

<table>
<thead>
<tr>
<th>UPPER EXTREMITIES</th>
<th>LOWER EXTREMITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>L</td>
</tr>
<tr>
<td>L</td>
<td>R</td>
</tr>
</tbody>
</table>

- **Deltoid C5, ankylosis**
- **Triceps C7, radial**
- **Biceps C5, 6, musculocutaneous**
- **Wrist Extension C6, radial**
- **Wrist Flexion C7, median**
- **Supraspinatus C3, supraspinatus**
- **Infraspinatus C3, supraspinatus**
- **Subscapularis C8, subscapularis**
- **Finger (Deyo's)**
- **Abdominals, thoraco-lumbar**

#### Range of Motion

<table>
<thead>
<tr>
<th>LEVEL OF RESTRICTION</th>
<th>normal (0-30%)</th>
<th>moderate restriction (30-50%)</th>
<th>marked restriction (&gt;50%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REGION</td>
<td>yes</td>
<td>no</td>
<td>Side and direction of motion</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>L</td>
<td>R</td>
</tr>
<tr>
<td>Cervical spine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thoracic spine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lumbar spine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hips</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knees</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Participant

<table>
<thead>
<tr>
<th>INCLUDED</th>
<th>EXCLUDED</th>
</tr>
</thead>
</table>

Reason for exclusion:

Signature:
Appendix 7: Health Questionnaire (English)

Date: …../……/…….. ID No.: ______________ PS

Health Questionnaire

Please take your time answering this questionnaire. If you have a question regarding any of the points, please ask one of the investigators prior to handing it in.

Demographics:  male ☐   female ☐
Age: _______ years

1.a. Have you ever suffered from any condition causing you dizziness or unsteadiness?  yes ☐ no ☐
1.b. Do you currently experience dizziness or unsteadiness?  yes ☐ no ☐

2. Have you ever sustained major trauma or surgery?  yes ☐ no ☐
If yes, please comment
________________________________________________________________________
________________________________________________________________________

3.a. Have you ever been involved in a serious road traffic accident where you were injured?  yes ☐ no ☐
3.b. If so, have you been diagnosed with Whiplash Associated Disorder?  yes ☐ no ☐
3.c. Have you been suffering from dizziness, nausea or headache as a consequence?  yes ☐ no ☐

4. Are you currently undergoing treatment for any heart condition?  yes ☐ no ☐
5. Are you currently undergoing treatment for high blood pressure?
yes ☐ no ☐

6.a. Have you ever been diagnosed with a disc prolapse or did you suffer from pain radiating down your legs?
yes ☐ no ☐

6.b. If yes, do you currently experience these symptoms?
yes ☐ no ☐

7.a. Have you been or are you currently suffering from altered sensation like tingling or numbness in any area?
yes ☐ no ☐

7.b. How long have you noticed it?
___ Years   ___Months   ___Weeks   ___Days

8. Have you, during sports or otherwise, sustained any leg or foot injuries, such as twisted ankle during the last 6 months?
yes ☐ no ☐

8.b. If yes, on which side?  right ☐ left   ☐ oth   ☐
If yes, was it severe? yes ☐ no ☐

9. Pain
If you have two main areas of complaint, you may indicate these by using the mark X and O on the scale.

Select the number that best describes your current pain intensity
(circle one number only)

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>No pain</td>
<td>Moderate pain</td>
<td>Worst possible pain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Please indicate the area you are referring to
X: _________________
O: _________________
10. On the graphic below, please indicate your currently most painful area(s) with a pen:

11.a. How many painful episodes of your current complaint have you experienced so far? Please give an estimate.

____ episodes

11.b. The pain you experienced was generally constant □ or intermittent □

11.c. Since it first started, the pain intensity

got worse □ got better □ remained constant □

12. Medication
Please indicate which medication you are currently taking

Pain □ Dizziness □ Neurological complaints □ Heart problems □

No medication □
Disability Questionnaire regarding daily physical activities

In addition to questions regarding your pain it is important to also assess the resulting disability to perform daily physical activities. For this purpose, the "Disability Rating Index" was developed.

On the next two pages you will be asked to indicate your perceived disability at this time to perform a selection of 12 activities by marking the line with a vertical stroke. The different grades of disability underneath are for general orientation purposes only. Depending on your perception you may set your mark at any point along the whole line. Two examples are shown below:

Should you have any further questions regarding this questionnaire, please contact the investigator before you begin filling it out.
Without difficulty  

**Dressing (without help)**  

Not at all  

<table>
<thead>
<tr>
<th>With some difficulty</th>
<th>With difficulty</th>
<th>With great difficulty</th>
</tr>
</thead>
</table>

Without difficulty  

**Outdoor walks**  

Not at all  

<table>
<thead>
<tr>
<th>With some difficulty</th>
<th>With difficulty</th>
<th>With great difficulty</th>
</tr>
</thead>
</table>

Without difficulty  

**Climbing stairs**  

Not at all  

<table>
<thead>
<tr>
<th>With some difficulty</th>
<th>With difficulty</th>
<th>With great difficulty</th>
</tr>
</thead>
</table>

Without difficulty  

**Sitting for a longer time**  

Not at all  

<table>
<thead>
<tr>
<th>With some difficulty</th>
<th>With difficulty</th>
<th>With great difficulty</th>
</tr>
</thead>
</table>

Without difficulty  

**Standing bend over a sink**  

Not at all  

<table>
<thead>
<tr>
<th>With some difficulty</th>
<th>With difficulty</th>
<th>With great difficulty</th>
</tr>
</thead>
</table>

Without difficulty  

**Carrying a bag**  

Not at all  

<table>
<thead>
<tr>
<th>With some difficulty</th>
<th>With difficulty</th>
<th>With great difficulty</th>
</tr>
</thead>
</table>
Without difficulty  |  Making a bed  |  Not at all
---|---|---
| With some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Running  |  Not at all
---|---|---
| With some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Light work  |  Not at all
---|---|---
| With some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Heavy work  |  Not at all
---|---|---
| With some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Lifting heavy objects  |  Not at all
---|---|---
| With some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Participating in exercise/sports  |  Not at all
---|---|---
| With some difficulty  |  With difficulty  |  With great difficulty
Appendix 9: Follow-up assessment form - English Version

ID No. PS_____________ Date: ____________ Follow-up No. 1 [ ] 2 [ ]

For administrative purposes only

1) Pain

1.a. On the scale below, please rate your pain intensity at this moment.

If you have two main areas of complaint, you may indicate these by using the mark X and O on the scale.

Select the number that best describes your current pain intensity (circle one number only)

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>No pain</td>
<td>Moderate pain</td>
<td>Worst possible pain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Please indicate the area you are referring to

X: _______________
O: _______________

1.b. Are you currently taking pain medication? Yes [ ] No [ ] [ ]

1.c. If yes, did you experience a resulting decrease in pain? Yes [ ] No [ ] [ ]

1.d. Were you able to reduced the dosage since the treatment started? Yes [ ] No [ ] [ ]

2) Treatment progress

Please rate the improvement you experienced since the beginning of the treatment(s) by marking the scale underneath with a vertical line.

This is not an assessment of your satisfaction with the treatment modalities or your chiropractor. It only aims to quantify the improvement you experience.
3) Disability assessment

In addition to questions regarding your pain it is important to also assess the resulting disability to perform daily physical activities. For this purpose, the "Disability Rating Index" was developed.

On the next two pages you will be asked to indicate your perceived disability at this time to perform a selection of 12 activities by marking the line with a vertical stroke. The different grades of disability underneath are for general orientation purposes only. Depending on your perception you may set your mark at any point along the whole line. Two examples are shown below:

Should you have any further questions regarding this questionnaire, please contact the investigator before you begin filling it out.
Without difficulty  |  Not at all
---|---
**Dressing (without help)**
|  |  |  
Without some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Not at all
---|---
**Outdoor walks**
|  |  |  
Without some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Not at all
---|---
**Climbing stairs**
|  |  |  
Without some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Not at all
---|---
**Sitting for a longer time**
|  |  |  
Without some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Not at all
---|---
**Standing bend over a sink**
|  |  |  
Without some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Not at all
---|---
**Carrying a bag**
|  |  |  
Without some difficulty  |  With difficulty  |  With great difficulty
Without difficulty  |  Making a bed  |  Not at all
---|---|---
With some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Running  |  Not at all
---|---|---
With some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Light work  |  Not at all
---|---|---
With some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Heavy work  |  Not at all
---|---|---
With some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Lifting heavy objects  |  Not at all
---|---|---
With some difficulty  |  With difficulty  |  With great difficulty

Without difficulty  |  Participating in exercise/sports  |  Not at all
---|---|---
With some difficulty  |  With difficulty  |  With great difficulty
Appendix 10: Information letter for potential healthy participants in the pilot and prospective studies

Information

Vielen Dank für Ihr Interesse an der Teilnahme am Forschungsprojekt "Die klinische Anwendung des Kraftangriffspunktes".

Die Versuche sind Teil des Doktorandenprogramms (PhD) von Alexander Ruhe (MChiro) und wurden von der Murdoch University in Perth (Australien) genehmigt.

Bevor wir Sie um Ihre Zustimmung bitten, möchten wir Sie umfassend informieren, damit Sie die Entscheidung über Ihre Teilnahme wohinformatiert treffen können. Sollten Sie zu irgendeinem Zeitpunkt zusätzliche Informationen benötigen, können Sie die Praxis jederzeit per Telefon oder email kontaktieren und einer der beteiligten Chiropraktoren wird sich Ihrer Fragen annehmen.

Wir hoffen, dass dieses Projekt nicht nur zum Grundverständnis von Veränderungen der Körperbalance im gesunden und pathologischen Zustand beiträgt, sondern auch eine frühzeitige Erkennung von Gleichgewichtsproblemen erlaubt, und damit einen Beitrag zur Sturz- und Verletzungsprävention leistet.

Der Versuchsaufbau beinhaltet, die Körperbalance durch Feststellung des natürlichen Schwankweges im Stehen zu messen. Dies erfolgt durch Ermittlung des Kraftangriffspunktes, der Stelle unter den Füßen, an dem sich der Druckpunkt des Körpergewichts befinden würde, wäre er auf eine Stelle zentriert. Wir werden Sie dazu bitten, auf einer Druckmessplatte zu stehen, während die Veränderungen des Kraftangriffspunktes aufgezeichnet werden.

Für die Messungen ist es erforderlich, dreimal für jeweils 90 Sekunden auf der Messplatte zu stehen. Diese Prozedur wird mit geschlossenen Augen durchgeführt. Der Zeitaufwand beträgt ungefähr 5-10 Minuten.

Alle Vorsichtsmaßnahmen werden getroffen, um Ihre Sicherheit zu gewährleisten. Für den unwahrscheinlichen Fall, dass sie auf der flachen Druckmessplatte das Gleichgewicht verlieren, stehen wir bereit, um sie zu stützen.

In äußerst seltenen Fällen kann es vorkommen, dass Sie sich bei einem Sturz verletzen. Desweiteren kann das Stehen mit verbundenen Augen bei bestimmten Personen Angst provozieren. In diesem Fall kann die Messung jederzeit unterbrochen werden.

Alle erhobenen Messdaten werden mit voller Vertraulichkeit behandelt. Ihnen wird hierzu eine individuelle Identifikationsnummer zugeteilt, die eine Zuordnung von Daten zu Ihrem Namen unmöglich macht. Nur die direkt an der Durchführung beteiligten Chiropraktoren haben Zugang zu den Messergebnissen oder jeglichen personenbezogenen Daten.
Alle erteilten Informationen und gesammelten Daten werden als vertraulich behandelt und
nicht an Dritte weitergeleitet, sofern keine gesetzliche Verpflichtung dazu entsteht.

Die Teilnahme an der Studie ist freiwillig. Sie können auch zu jedem Zeitpunkt Ihre Meinung
ändern und von der Teilnahme zurücktreten.

Keine kommerziellen oder nicht kommerziellen Sponsoren sind an dieser Studie beteiligt und
keiner der beteiligten Forscher erhält finanzielle Zuwendungen jedweder Art. Desweiteren
erfolgt keine finanzielle Aufwandsentschädigung für die Teilnehmer.

Dieses Forschungsprojekt wird in Einklang mit dem "National Statement on Ethical Conduct in
Research involving Humans" (Australien), den Ethik-Richtlinien der Murdoch University für die
Durchführung von Forschungsstudien, sowie der "Deklaration von Helsinki" des
Weltärztebundes bezüglich ethischer Prinzipien für medizinische Studien mit Menschen
durchgeführt.

Sollten Sie bezüglich dieser Studie eine Beschwerde einreichen wollen, so können Sie dies
die Zeit bei der Ethikkommission der Murdoch University tun. Ihre Beschwerde kann dabei in
Deutsch gehalten sein. Die Kontaktdresse ist:

Research Ethics Office
Division of Research and Development
Chancellery Building
South Street
MURDOCH WA 6150

Telefon: 0061-8-9360 6677
Fragen sie nach Dr Erich von Dietze
human.ethics@murdoch.edu.au

Falls Sie zu dieser wichtigen Forschungsstudie betragen möchten, kontaktieren sie bitte die
Praxis unter:

Praxis für Chiropraktik Wolfsburg
Porschestraße 1
38440 Wolfsburg
Telefon: 05361- 8481358
Fax: 05361 - 8481378
info@chiropraktik-wolfsburg.de

Danke, dass Sie sich die Zeit zum Lesen dieser Informationen genommen haben, bei
weiteren Fragen zögern sie bitte nicht, einen der Chiropraktoren zu kontaktieren.

Diese Studie wurde von der Ethik-Kommission der Murdoch University genehmigt (Erlaubnis 2010/066). Sollten Sie
irgendetwelche Bedenken oder Beschwerden in Bezug auf die ethische Durchführung dieser Studie haben und
möchten diesbezüglich Kontakt zu einer unabhängigen Person aufnehmen, können Sie das Büro für
Forschungsethik der Murdoch University (Tel. 0061-8-9360 6677 oder email: ethics@murdoch.edu.au) kontaktieren.
Alle Belange werden vertraulich behandelt und gründlich geprüft. Sie werden über den Ausgang der Untersuchung
informiert.
Vielen Dank für Ihr Interesse an der Teilnahme am Forschungsprojekt

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Der zusätzliche Zeitaufwand beträgt ungefähr 15 Minuten für die erste Sitzung und 10 Minuten für nachfolgende Messungen. Eine Teilnahme beinhaltet die Bereitschaft zu zwei Folgemessungen, die um Ihre normalen Behandlungstermine herum arrangiert werden. Sie können die Teilnahme jedoch zu jedem Zeitpunkt abbrechen.

Alle Vorsichtsmaßnahmen werden getroffen, um Ihre Sicherheit zu gewährleisten. Für den unwahrscheinlichen Fall, dass sie auf der flachen Druckmessplatte das Gleichgewicht verlieren, stehen wir bereit, um sie zu stützen.

In äußerst seltenen Fällen kann es vorkommen, dass Sie sich bei einem Sturz verletzen. Desweiteren kann das Stehen mit verbundenen Augen bei bestimmten Personen Angst provozieren. In diesem Fall kann die Messung jederzeit unterbrochen werden.
Alle erhobenen Messdaten werden mit voller Vertraulichkeit behandelt. Ihnen wird hierzu eine individuelle Identifikationsnummer zugeteilt, die eine Zuordnung von Daten zu Ihrem Namen unmöglich macht. Nur die direkt an der Durchführung beteiligten Chiropraktoren haben Zugang zu den Messergebnissen oder jeglichen personenbezogenen Daten.

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Research Ethics Office  
Division of Research and Development  
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Diese Studie wurde von der Ethik-Kommission der Murdoch University genehmigt (Erlaubnis 2010/066). Sollten Sie irgendwelche Bedenken oder Beschwerden in Bezug auf die ethische Durchführung dieser Studie haben und möchten diesbezüglich Kontakt zu einer unabhängigen Person aufnehmen, können Sie das Büro für Forschungsethik der Murdoch University (Tel. 0061-8-9360 6677 oder email: ethics@murdoch.edu.au) kontaktieren. Alle Belange werden vertraulich behandelt und gründlich geprüft. Sie werden über den Ausgang der Untersuchung informiert.
Einverständniserklärung

Ich habe den Inhalt des Informationsbriefes bezüglich der Forschungsstudie "Die klinische Anwendung des Kraftangriffspunktes" vollständig gelesen und verstanden.

7. Ich nehme freiwillig an dieser Studie teil.


10. Meine Identität wird in keiner aus dieser Studie resultierenden Veröffentlichung preisgegeben.

11. Mein Name und Identität wird von den Messdaten separat aufbewahrt und ist nur für die Forscher zugänglich. Alle Daten werden anonymisiert unter Verwendung einer Identifikationsnummer ausgewertet.

12. Alle erteilten Informationen und gesammelten Daten werden als vertraulich behandelt und werden nicht an Dritte weitergeleitet, solange keine gesetzliche Verpflichtung dazu entsteht.

Name (in Druckbuchstaben): _____________________________________________________

Unterschrift des Teilnehmers: ______________________________ Date: ……/……/……

Unterschrift des Chiropraktors: ______________________________ Date: ……/……/……

Ich möchte nach Beendigung der Studie über die Ergebnisse informiert werden [ ] (bitte ankreuzen)

Diese Studie wurde von der Ethik-Kommission der Murdoch University genehmigt (Erlaubnis 2010/066). Sollten Sie irgendwelche Bedenken oder Beschwerden in Bezug auf die ethische Durchführung dieser Studie haben und möchten diesbezüglich Kontakt zu einer unabhängigen Person aufnehmen, können Sie das Büro für Forschungsethik der Murdoch University (Tel. 0061-8-9360 6677 oder email: ethics@murdoch.edu.au) kontaktieren. Alle Belange werden vertraulich behandelt und gründlich geprüft. Sie werden über den Ausgang der Untersuchung informiert.
Appendix 13: Health Questionnaire (German)

Datum: ……/……/…….
ID Nr.: _______________ PS

Fragebogen zur Gesundheit

Bitte nehmen Sie sich die Zeit, diesen Fragebogen vollständig auszufüllen. sollten sie irgendwelche Fragen dazu haben, kontaktieren sie bitte einen der Chiropraktoren vor der Abgabe.

Geschlecht: männlich □ weiblich □

Alter: ______ Jahre

1.a. Haben sie zu irgendeinem Zeitpunkt unter Schwindel oder unsicherem Stand/Gang gelitten?
Ja □ Nein □ (1: ja, 0: nein)

1.b. Leiden Sie momentan unter Schwindel oder unsicherem Stand/Gang?
Ja □ Nein □

2. Hatten Sie jemals einen schweren Unfall oder größere Operationen?
Ja □ Nein □

Fall ja, bitte beschreiben Sie:

________________________________________________________________________
________________________________________________________________________

3.a. Hatten sie jemals einen schweren Verkehrsunfall und wurden dabei verletzt?
Ja □ Nein □

3.b. Falls ja, wurde bei Ihnen ein Schleudertrauma diagnostiziert?
Ja □ Nein □

3.c. Haben Sie in der Folge unter Schwindel, Übelkeit oder Kopfschmerzen gelitten?
Ja □ Nein □

4. Werden sie momentan für Herzprobleme behandelt?
Ja □ Nein □
5. Sind sie momentan für Bluthochdruck in Behandlung?
Ja ☐ Nein ☐

6.a. Wurde bei Ihnen zuvor ein Bandscheibenvorfall diagnostiziert, oder litten Sie unter bis in die Beine ausstrahlenden Schmerzen?
Ja ☐ Nein ☐

6.b. Fall ja, bestehen die Symptome momentan?
Ja ☐ Nein ☐

7.a. Spüren Sie momentan Gefühlsveränderungen wie Kribbeln oder Taubheit in irgendeiner Körperregion, oder war dies in der Vergangenheit der Fall?
Ja ☐ Nein ☐

Falls Sie die Gefühlsveränderungen momentan spüren, zeichnen Sie den fraglichen Bereich bitte auf der Grafik in Abschnitt 10 ein.

7.b. Wie lange bemerken Sie diese Gefühlsveränderungen bereits?
___ Jahre ___Monate ___Wochen ___Tage

8.a. Haben sie sich in den letzten 6 Monaten an Bein oder Fuß verletzt (z.B. den Knöchel verstaucht)?
Ja ☐ Nein ☐


Sollten sie zwei Hauptbeschwerden haben, können Sie diese mit einem X und O auf der Skala markieren.

Wählen Sie bitte die Zahl, die Ihre momentane Schmerzintensität am besten beschreibt.
(Please wählen Sie nur eine Nummer)

<table>
<thead>
<tr>
<th>0</th>
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<tr>
<td>Kein Schmerz</td>
<td>Mittelmäßige Schmerzen</td>
<td>Stärkster möglicher Schmerz</td>
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</tbody>
</table>

Bitte beschreiben Sie den Bereich, auf den Sie sich beziehen:

X: _____________________

O: _____________________
10. Auf der untenstehenden Grafik, zeichnen Sie bitte nur Ihren momentan schmerzhaftesten Bereich ein.

___ Episoden

11.b. Der Schmerz tritt dabei □ konstant oder □ periodisch auf  (1: konstant, 2: periodisch)

11.c. Seit dem ersten Auftreten hat sich die Schmerzintensität
□ verschlimmert □ verbessert □ ist konstant geblieben  (1: verschlimmert, 2: verbessert, 3: konstant)

12. Medikamente
Bitte kreuzen sie an, ob Sie momentan Medikamente für die folgenden Beschwerden nehmen:
□ Schmerzen □ Schwindel □ neurologische Beschwerden □ Herzprobleme
□ keine Medikamente  (0: keine, 1: Schmerzen, 2: Schwindel, 3: Neurologisch, 4: Herz)
Fragebogen zu Einschränkungen bei täglichen Aktivitäten

Neben Fragen, die sich mit Ihren Schmerzen befassen, ist es wichtig, einen Überblick über die resultierenden Einschränkungen im alltäglichen Leben zu erhalten. Zu diesem Zweck der "Disability Rating Index" entwickelt, dessen deutsche Ausführung Ihnen nun vorliegt.

Bitte markieren Sie zu den 12 auf den nächsten zwei Seiten folgenden Beispielaktivitäten Ihre momentane Einschränkung mit einem senkrechten Strich auf der Linie. Die aufgeführten verschiedenen Einschränkungsstufen darunter dienen nur der allgemeinen Orientierung, bitte entscheiden sie ihrem Eindruck entsprechend frei entlang der Linie. Untenstehend sind hierzu zwei Beispiele aufgeführt:

Sollten Sie zu den Bögen noch weitere Fragen haben, stellen sie diese bitte bevor Sie mit dem Ausfüllen beginnen.
Ohne Schwierigkeiten: Anziehen (ohne Hilfe)

Ohne Schwierigkeiten: Spaziergänge draußen

Ohne Schwierigkeiten: Treppensteigen

Ohne Schwierigkeiten: Sitzen für längere Zeit

Ohne Schwierigkeiten: Vornübergebeugt am Waschbecken stehen

Ohne Schwierigkeiten: Eine Tasche tragen

Nicht möglich
Ohne Schwierigkeiten: Ein Bett machen
Nicht möglich

Ohne Schwierigkeiten: Laufen
Nicht möglich

Ohne Schwierigkeiten: Leichte Arbeit
Nicht möglich

Ohne Schwierigkeiten: Schwere Arbeit
Nicht möglich

Ohne Schwierigkeiten: Heben schwerer Gegenstände
Nicht möglich

Ohne Schwierigkeiten: Teilnahme an sportlichen Aktivitäten
Nicht möglich
1) Schmerzen

1.a. Bestimmen Sie bitte auf der Skala unten Ihre Schmerzintensität zu diesem Zeitpunkt.

Sollten Sie zwei Hauptbeschwerden haben, markieren Sie die jeweilige Schmerzintensität bitte mit X und O.

Wählen Sie bitte die Zahl, die Ihre momentane Schmerzintensität am besten beschreibt.
(Bitten wählen Sie nur eine Nummer)

<table>
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</tr>
</tbody>
</table>

Bitte beschreiben den Bereich, auf den Sie sich beziehen:

X: ____________________
O: ____________________

1.b. Nehmen Sie momentan Schmerzmittel?  □ Ja  □ Nein (1: ja, 0: nein)

1.c. Falls ja, kam es dadurch zu einer Schmerzminderung?  □ Ja  □ Nein

1.d. Haben Sie seit Beginn der Behandlung die Schmerzmittelstosis verringert?  □ Ja  □ Nein

2) Bewertung des Behandlungserfolges

Bitte beschreiben Sie den bisherigen Behandlungserfolg, indem Sie die untenstehende Linie mit einem senkrechten Strich an der entsprechenden Stelle markieren.

Dies ist keine Bewertung Ihrer Zufriedenheit mit der Behandlungsmethode selbst oder Ihrem Chiropraktor, sondern zielt einzig auf die von Ihnen wahrgenommene Besserung ab.

Keine Besserung  | Vollkommene Besserung
---|---

ID Nr. PS_____________ Datum: _____________ Folgeuntersuchung Nr. 1 □  2 □
3) Bewertung der Einschränkung bei Alltagsaktivitäten

Fragebogen zu Einschränkungen bei täglichen Aktivitäten
Neben Fragen, die sich mit Ihren Schmerzen befassen, ist es wichtig, einen Überblick über die resultierenden Einschränkungen im alltäglichen Leben zu erhalten. Zu diesem Zweck der "Disability Rating Index" entwickelt, dessen deutsche Ausführung Ihnen nun vorliegt.

Bitte markieren Sie zu den 12 auf den nächsten zwei Seiten folgenden Beispielaktivitäten Ihre momentane Einschränkung mit einem senkrechten Strich auf der Linie. Die aufgeführten verschiedenen Einschränkungsstufen darunter dienen nur der allgemeinen Orientierung, bitte entscheiden sie ihrem Eindruck entsprechend frei entlang der Linie. Untenstehend sind hierzu zwei Beispiele aufgeführt:

Sollten Sie zu den Bögen noch weitere Fragen haben, stellen sie diese bitte bevor Sie mit dem Ausfüllen beginnen.
Ohne Schwierigkeiten | Anziehen (ohne Hilfe) | Nicht möglich

Ohne Schwierigkeiten | Spaziergänge draußen | Nicht möglich

Ohne Schwierigkeiten | Treppensteigen | Nicht möglich

Ohne Schwierigkeiten | Sitzen für längere Zeit | Nicht möglich

Ohne Schwierigkeiten | Vornübergebeugt am Waschbecken stehen | Nicht möglich

Ohne Schwierigkeiten | Eine Tasche tragen | Nicht möglich
Ohne Schwierigkeiten | \textit{Ein Bett machen} | Nicht möglich

Ohne Schwierigkeiten | \textit{Laufen} | Nicht möglich

Ohne Schwierigkeiten | \textit{Leichte Arbeit} | Nicht möglich

Ohne Schwierigkeiten | \textit{Schwere Arbeit} | Nicht möglich

Ohne Schwierigkeiten | \textit{Heben schwerer Gegenstände} | Nicht möglich

Ohne Schwierigkeiten | \textit{Teilnahme an sportlichen Aktivitäten} | Nicht möglich
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The test–retest reliability of centre of pressure measures in bipedal static task conditions – A systematic review of the literature

Alexander Ruhe, René Fejer, Bruce Walker

Summary of background data: The analysis of centre of pressure (COP) excursions is used as an index of postural stability in standing. Conflicting data have been reported over the past 20 years regarding the reliability of COP measures and no standard procedure for COP measure use in study design has been established.

Search methods: Six online databases (January 1980 to February 2009) were systematically searched followed by a manual search of retrieved papers.

Results: Thirty-two papers met the inclusion criteria. The majority of the papers (26/32, 81.3%) demonstrated acceptable reliability. While COP mean velocity (mVel) demonstrated variable but generally good reliability throughout the different studies ($r = 0.32–0.94$), no single measurement of COP appeared significantly more reliable than the others. Regarding data acquisition duration, a minimum of 90 s is required to reach acceptable reliability for most COP parameters. This review further suggests that while eyes closed readings may show slightly higher reliability coefficients, both eyes open and closed setups allow acceptable readings under the described conditions ($r \geq 0.75$). Also averaging the results of three to five repetitions on firm surface is necessary to obtain acceptable reliability. A sampling frequency of 100 Hz with a cut-off frequency of 10 Hz is also recommended. No final conclusion regarding the feet position could be reached.

Conclusions: The studies reviewed show that bipedal static COP measures may be used as a reliable tool for investigating general postural stability and balance performance under specific conditions. Recommendations for maximizing the reliability of COP data are provided.

Keywords: Centre of pressure, Force-plate, Reliability, Systematic review

1. Background

Postural stability is an important component in maintaining an upright position and in maintaining balance during normal daily movements and activities. Postural stability is also an important factor in the elderly where balance disability may increase the risk of falls and subsequent injury. In sport, problems with balance may lead to serious injuries [1]. Thus, postural stability has important implications in sports and rehabilitation. Many different methods exist today for assessing postural stability. The evaluation of parameters describing COP excursions is a frequently used method of measuring this stability and any associated pathological mechanisms. This is possible as the COP signal is proportional to ankle torque, a combination of descending motor commands as well as mechanical properties of the surrounding musculature [2]. Measurements are most commonly evaluated by using spatial measures such as sway distance, velocity and area traversed based upon sequential locations of the COP in the plane of the force platform.

Many factors contributing to postural control have been identified. This postural control system depends on the unpaired ability to correctly perceive the environment through peripheral sensory systems, as well as to process and integrate vestibular, visual and proprioceptive inputs at the central nervous system (CNS) level. Depending on whether the task at hand is static or dynamic in nature, the CNS employs different strategies to form appropriate muscle synergies needed to maintain equilibrium [3]. In addition to individual perceptual and motor skills, the area of support in terms of foot position, musculoskeletal characteristics and task constraints play an important role in postural stability.

The methods of measurement of human standing posture can be broadly classified into three main groups: (1) body segment displacement during standing posture, (2) muscle activity for maintaining postural equilibrium, and (3) measurement of the movement and patterns of the centre of mass (COM) or centre of pressure (COP) [3].

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ABSTRACT

Summary of background data: The analysis of centre of pressure (COP) excursions is used as an index of postural stability in standing. Conflicting data have been reported over the past 20 years regarding the reliability of COP measures and no standard procedure for COP measure use in study design has been established.

Search methods: Six online databases (January 1980 to February 2009) were systematically searched followed by a manual search of retrieved papers.

Results: Thirty-two papers met the inclusion criteria. The majority of the papers (26/32, 81.3%) demonstrated acceptable reliability. While COP mean velocity (mVel) demonstrated variable but generally good reliability throughout the different studies ($r = 0.32–0.94$), no single measurement of COP appeared significantly more reliable than the others. Regarding data acquisition duration, a minimum of 90 s is required to reach acceptable reliability for most COP parameters. This review further suggests that while eyes closed readings may show slightly higher reliability coefficients, both eyes open and closed setups allow acceptable readings under the described conditions ($r \geq 0.75$). Also averaging the results of three to five repetitions on firm surface is necessary to obtain acceptable reliability. A sampling frequency of 100 Hz with a cut-off frequency of 10 Hz is also recommended. No final conclusion regarding the feet position could be reached.

Conclusions: The studies reviewed show that bipedal static COP measures may be used as a reliable tool for investigating general postural stability and balance performance under specific conditions. Recommendations for maximizing the reliability of COP data are provided.

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Body segment displacement refers to the change in position of body segments such as head or trunk during adaptive movements in order to maintain balance [4]. During balance control, the muscle action appears to be an anticipatory feed-forward mechanism that is determined by an internal model of the inverted pendulum and acts in the long-term. It aims at stopping the fall and pushes the body back towards its reference point [2].

In contrast, the intrinsic feedback due to mechanical properties of ankle muscles operates with a zero delay in the short-term in order to slow down the fall of the inverted pendulum. The inverted pendulum model relates the controlled variable (COM) with the controlling variable (COP) [5]. The complementation of this mechanism by the feed-forward control is necessary as the muscle stiffness itself is not sufficient to stabilize the body if the critical level of displacement is reached [2].

COP can be defined as the position of the global ground reaction force vector that accommodates the sway of the body. In simple terms, it is the point at which the pressure of the body over the soles of the feet would be if it were concentrated in one spot. This measure, however, is not a true record of body sway but rather a measure of the activity of the motor system in moving the COP. Centre of mass (COM) is a point equivalent of the total body mass in the global reference system and is commonly accepted to lie around the S2 vertebral level in normal upright posture [6]. Lafond et al. [7] demonstrated the relationship between COP and COM during stance, where COP oscillates on either side of the COM. While COP theoretically completely coincides with COM at low sway frequencies below 1 Hz [4], its displacement during sway always exceeds that of the COM [7].

Of these, one of the most commonly used tools to investigate this complex balance system is the stabilogram, which is a measure of the time behaviour of the COP of a person positioned on top of a force platform consisting of a rigid plate supported by force transducers.

Postural sway observed in quiet standing represents the integrated output from the complex interaction between the balance systems mentioned above. As understanding of these balance mechanisms evolved over the last decades, the literature shows a large change in study designs and instruments used to investigate COP.

While the evaluation of COP excursions is a commonly used method for measuring postural stability [21–38] no standardization of this method exists. Further, the reliability of COP needs to be determined if studies using this method are to be considered valid. To our knowledge no systematic literature review has been conducted to investigate the reliability of COP measures.

2. Aims

The aims of this systematic literature review are (1) to describe and assess the methodological procedures of studies of the most commonly used COP measurements and methods, (2) to determine the reliability of commonly used centre of pressure measures in bipedal static task conditions, and (3) to provide recommendations regarding standardized COP methods for future use in study designs.

3. Methods

3.1. Search strategy

A comprehensive search strategy was developed by identifying all potentially relevant search terms, categorizing these terms into specific search phases and subsequently combining them by using Boolean terms. This search strategy was designed to be used in six different electronic databases. These were PubMed, MEDLINE, EMBASE, Web of Science, ScienceDirect, Digital Dissertations and the Cochrane library. The search strategy is available upon contacting the corresponding author.

3.2. Electronic searches

All databases were searched using the search strategy described above. Appropriate minor modifications to the basic search template were made to optimize the strategy in individual databases. Papers were limited to human studies published between January 1980 and February 2009.

3.3. Searching other resources

The hand search included analyzing references cited in studies selected from the original online search. Citation searches of relevant studies were conducted using the PubMed, MEDLINE and ScienceDirect databases.

3.4. Selection criteria

Articles were limited to peer-reviewed journals and dissertations without restrictions regarding language. Wide inclusion and exclusion criteria for study designs were used in order to avoid limitation of potentially relevant papers.

The inclusion criteria were: articles that were fully or partially concerned with the intra- and intersession reliability of COP data derived from bipedal static tasks on a force plate. For this systematic review, all COP measures, experimental setups and statistical models fitting these criteria were considered. No limitations of the type of patient demographics or health status applied.

We excluded studies with insufficient documentation of patient demographics or experimental setup. In addition, papers that were anecdotal, speculative or editorial in nature or studies that employed dynamic task conditions such as one-leg hopping, walking or some form of translation of the force platform were excluded.

If any title and abstract did not provide enough information to decide whether or not the inclusion criteria were met, the full text of the article was obtained.

3.5. Data extraction and management

For the purpose of this review AR acted as the principal reviewer. A colleague (TB) was involved independently in the process of identifying relevant studies and did not participate in further analysis of the finally included papers. A third reviewer (AS) was used for a majority decision in case discrepancies between AR and TB were not reconciled by discussion. To standardize the procedure between the reviewers, the principal reviewer developed a detailed protocol sheet for critical appraisal by which general information on objectives, design, participant’s demographics and outcomes were extracted. Each reviewer retrieved the information independently. A test was conducted with two articles similar but unrelated to the review question and the procedures discussed.

3.6. Assessment of methodological procedures

The reviewers specifically assessed the application, documentation and association of six individual items with regards to test-retest reliability. These were (1) subject demographics and morphology, (2) sample duration, (3) number of trial repetitions,
(4) visual condition (eyes open/eyes closed), (5) foot position, and (6) type of platform surface. Papers not describing the items need to be considered with caution as these are necessary for full understanding and appreciation of the reliability study. The rationale for choosing these factors was based on the fact that they were considered particularly relevant for reliability outcomes by the available literature (e.g. [30–38]).

4. Results

4.1. Literature search results

Initially, the online search strategy identified 215 study abstracts which were screened individually by the reviewers. The application of inclusion/exclusion criteria by the reviewers on the titles and abstracts eliminated a further 162 papers. The most common reason for exclusion was not meeting the selection criteria like static or bipedal tasks. From the titles and abstracts of papers selected (n = 53), full articles were reviewed and the same two reviewers (AR and TB) applied the inclusion criteria to the full text. Of these, 32 papers met the inclusion criteria and were included in this review. Eleven of these articles were added after the hand search of reference lists of included papers.

The selection process of suitable studies identified only minor variance between the reviewers. AR and TB initially disagreed on the inclusion of two papers, giving an overall agreement of 97%. The differences were documented and consensus reached after discussion.

4.2. Study results

4.2.1. Characteristics of participants and methods

About 30% of the studies (9/32) provided either insufficient description of the selection criteria for participants or none at all. No study described blinding of the examiners to the subject’s health status.

While about half the authors described the baseline demographics in appropriate detail (18/32, 56%), only one study included a physical examination in order to validate their health status prior to study enrollment [8]. The other authors relied only on self-reports or did not provide any description at all. Only four studies reported calibration procedures of the force-plate, mostly by means of a calibrated static load [9–12]. With regard to patient demographics, most studies (83%) enrolled mixed gender groups of healthy participants between 21 and 40 years of age. Subject demographics and health status for all studies is shown in Table 1.

In order to challenge postural control by modifying the integration of visual, vestibular or proprioceptive input, the included studies variously applied a selection or a combination of all three conditions (eyes open/eyes closed, firm/compliant surface, narrow/normal stance). About 78% of the trials were performed under both eyes closed (EC) and eyes open (EO) conditions. Most authors conducted between 2 and 5 repetitions of postural sway recordings (14/32, 44%). In addition, the majority of trials were conducted on the firm surface (26/32, 81%) of a force platform (see Table 2).

5. The statistics

As with the general experimental setups, an equally heterogeneous selection of statistics for describing the reliability was used, including the coefficient of variation (CV), generalizability coefficient (GC) as well as Pearson's correlation coefficient (PCC). The most commonly applied statistic however, were the different forms of the intraclass correlation coefficient (ICC). While most used models described originally by Shrout and Fleiss [13], others again employed modified versions [14]. About 30% (6/22) of the studies using the ICC failed to state the exact model used. The corresponding authors of these studies were contacted in order to gather the missing information but only two replies [14,15] were received. Where ICC models were reported, the two-way random effect model (ICC2,1) was employed most often. Two studies [16,17] used the related generalizability theory.

6. Relationships between methods and reliability

While various studies have investigated the same COP parameters such as mean velocity or area of sway, an inter-study comparison of each parameter's individual reliability is often problematic because of differences in study designs. Only a few studies offer similar experimental procedures that allow for comparing the effect of various factors on the reliability of COP measures (Tables 3a–3c).

7. Discussion

7.1. General considerations

Due to the heterogeneous study designs and statistical models used there remains little common ground for combining the reliability of all data presented. Only a few papers allowed for direct inter-study comparison of results and most of the conclusions had to be drawn from those studies. No quantitative pooling of results from the studies was possible, but we were nevertheless able to extract enough information to make recommendations regarding reliable experimental setups for COP measurements.

Many trials on the reliability of COP measures were conducted as a complimentary part of papers concerned with postural control and as such COP did not appear in the title or keyword lists. Our search strategy aimed to address that problem; in addition, selected hand searches of reference lists were necessary to identify some of the relevant papers. However, of those studies none contributed any new information to the discussion. It may be therefore safely assumed that as the vast majority of papers were included, no implications regarding the overall conclusions arise.

With regards to differences between within-day and between-day reliabilities, it has been shown that trials run on the same day yield higher values [10,14]. While intra-trial and inter-trial reliability needs to be discussed, inter-rater reliability is unlikely to be of concern due to the simplicity of the apparatus, task and instructions. It appears, however, that it was this simplicity that has led to a lack of standardization in operation.

When considering potential sources of variability affecting the reliability of COP measures one may distinguish between effects of the measurement procedures themselves that can be controlled (e.g. sampling duration, signal processing) and sources of variability that may not (e.g. joint/muscle function). Generally, the inter-subject variability may be at least partially explained by the learning effect observed [12], leading to an optimization of energy expenditure by progressively reducing body sway over the course of repetitions.

7.2. Choice of statistics

The choice of statistics has a profound effect on the reliability results of identical data sets – with subsequent consequences for the interpretation. The most commonly applied statistical tests were different models of the intra-class correlation coefficient (ICC) [13] and the coefficient of variation (CV). Two studies [18,19] employed Pearson’s correlation coefficients (PCC) although its
application in test–retest reliability studies is often discouraged for its inability to detect systematic error [20].

There are numerous versions of the ICC described in the literature some of which were employed in the presented studies. The ICC is a ratio of variances deriving from ANOVA that is unitless and theoretically varies between 0.0 and 1.0. For the purpose of this application in test–retest reliability studies is often discouraged for its inability to detect systematic error [20].

As it will be seen later on in the discussion, the magnitude of the ICC is dependent on the variability of the COP data. The heterogeneity of the participants therefore needs to be carefully considered, as high ICC values may mask poor test–retest consistency if there is a large variability between the participants as it would be expected, for example, in the elderly. Conversely, even in the presence of low inter-participant variability, small test–retest variations may cause low ICC value [20,21].

Tables 3a–3c show that results of the related models ICC2,1 and ICC2,3 are very similar. This also accounts for many of the values from different formulae will be similar. This can be observed in Tables 3b when comparing the values reported by Lafond et al. [22] and Carpenter et al. (ICC3,k) [15].

In conclusion, it needs to be kept in mind that while the variations resulting from different statistics may be marginal as it would be expected, for example, in the elderly. Conversely, even in the presence of low inter-participant variability, small test–retest variations may cause low ICC value [20,21].

### Table 1

<table>
<thead>
<tr>
<th>Study</th>
<th>Number</th>
<th>Gender</th>
<th>Age plus range</th>
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<th>Height (cm)</th>
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<tr>
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<td>28</td>
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<tr>
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<tr>
<td>Le Clar et al., 1995 [45]</td>
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<td>B: 30</td>
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<td>23–60</td>
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</tr>
<tr>
<td>Mattacola et al., 1995 [49]</td>
<td>12</td>
<td>10</td>
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<td>24.7 ± 3</td>
<td>62.2 ± 7.5</td>
<td>164.8 ± 7</td>
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<td>Riley et al., 1995 [19]</td>
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<td>7</td>
<td>50.3</td>
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<tr>
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</tr>
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<td>Moe-Nilssen, 1998 [52]</td>
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<tr>
<td>Benvenuti et al., 1999 [12]</td>
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<th>Parameters</th>
<th>Duration (s)</th>
<th>Repetitions</th>
<th>Statistics</th>
<th>Results</th>
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<tr>
<td>Goldie et al., 1989 [44]</td>
<td>BP, tandem, EO/EC/F, narrow stance</td>
<td>COP Ml/AP Force AP/Ml/vertical</td>
<td>32</td>
<td>2</td>
<td>LR</td>
<td>EO: Ml 0.30, AP 0.11</td>
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<td>Hageman et al., 1995 [10]</td>
<td>BP, EO/EC/F, normal stance</td>
<td>COP sway area</td>
<td>20</td>
<td>2</td>
<td>ICC 4</td>
<td>EO: 0.91, EC: 0.97</td>
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<tr>
<td>Hill et al., 1995 [42]</td>
<td>BP, EO/F, normal, narrow stance+ others</td>
<td>Dispersion Index (D1)</td>
<td>25</td>
<td>9 × 3</td>
<td>ICC 2.1 CV</td>
<td>EO: normal Kc 0.55, CV 0.17, narrow ICC 0.27, CV 0.19</td>
</tr>
<tr>
<td>Le Ciar et al., 1995 [45]</td>
<td>BP, normal stance EO/EC/F</td>
<td>SD COP Ml/AP, mVel, SD force AP/Ml/vertical</td>
<td>10, 20, 30, 40, 50, 60</td>
<td>2</td>
<td>RC</td>
<td>SD Ml: 0.81, SD AP: 0.86, mVel: 0.84</td>
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<tr>
<td>Letz et al., 1995 [21]</td>
<td>BP, narrow, EC/EO/F</td>
<td>Vel, SD path, RMS AP/Ml, mean excursion AP/Ml</td>
<td>60 (2 × 30)</td>
<td>2</td>
<td>PCC</td>
<td>SD/EC/F 60s: RMS path AP/Ml 0.28–0.79, SD range 0.50–0.83, Vel 0.85–0.92</td>
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<td>Sway index</td>
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<td>10</td>
<td>ICC (unclear)</td>
<td>EO: ICC 0.75, SEM 0.06, 95% CI 0.16–0.40 EC: ICC 0.06, SEM 0.26, 95% CI 0.13–0.87</td>
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<td>PCC</td>
<td>Healthy subjects: COP ML 0.91, AP 0.78</td>
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<td>Mean velocity</td>
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<td>10</td>
<td>CV (%)</td>
<td>EO: 9.46% (4.55–29.38), EC: 10.53% (3.68–24.28)</td>
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<tr>
<td>Takala et al., 1997 [51]</td>
<td>BP, EO/EC/F narrow stance</td>
<td>Mean Vel, area, frequency, amplitude</td>
<td>30</td>
<td>2 × 2</td>
<td>ICC (unclear)</td>
<td>Short term: ED mVel 0.64, EC 0.50, area ED 0.55, EC 0.43. Long term: ED mVel 0.86, EC 0.77, area ED 0.44, EC 0.40</td>
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<td>Moe-Nilssen, 1998 [52]</td>
<td>BP, EO/EC/F narrow stance</td>
<td>RMS AP/Ml</td>
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<td>3</td>
<td>ICC 4</td>
<td>All parameters ICC &lt;0.60 ED/EC, CV (%) 19.2–25.2</td>
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<tr>
<td>Benvenuti et al., 1999 [12]</td>
<td>BP, LB/NB, F/C, EO/EC</td>
<td>Mean velocity, Quadratic fit AP/Ml/MP/AMl RMS amplitude, RMS velocity</td>
<td>40 (15 recorded)</td>
<td>3</td>
<td>ICC 3, CV (%)</td>
<td>Vel 0.51–0.75, Ml 0.65–0.77, AP 0.82–0.83</td>
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<tr>
<td>Geurts et al., 1999 [47]</td>
<td>A:B, EO/EC/BV B: BP, EO/EC F/C, normal stance</td>
<td>Unclear</td>
<td>30</td>
<td>3 ICC 2,1 CV</td>
<td>RMS area: Ml 36%, AP 63%, EC 57%, AP 20%, range Ml 32%, AP 27%</td>
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<td>Mientjes et al., 1995 [48]</td>
<td>BP, normal stance, EO/EC/F</td>
<td>AP/Ml RMS, COP mean, MPF</td>
<td>Unclear</td>
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<td>ICC (unclear)</td>
<td>EO: RMS AP 0.14, ML 0.54, EC: RMS AP 0.41, ML 0.89</td>
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<tr>
<td>Carpenter et al., 2000 [17]</td>
<td>BP, narrow stance, EO/EC/F</td>
<td>RMS, MF, MP, PO/Ml/AP/Ml</td>
<td>120 (8 × 15, 4 × 30, 2 × 60)</td>
<td>3</td>
<td>ICC 8</td>
<td>Pos Ml 0.32–0.73, AP 0.32–0.77</td>
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<tr>
<td>Chiari et al., 2000 [38]</td>
<td>BP, normal stance EO/EC/F</td>
<td>mVel, FD, area, Diffusion and Hurst coefficient (H)</td>
<td>50</td>
<td>10</td>
<td>ICC (modified)</td>
<td>mVel EO 0.83, EC 0.87, area ED 0.58, EC 0.70, FD EO 0.53, EC 0.80, SD MP 0.30–0.79, NSMP 0.54–0.85</td>
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<td>BP, EO/F, normal stance</td>
<td>mVel, area, amplitude, MPF, Hurst</td>
<td>Unclear</td>
<td>3</td>
<td>ICC 3</td>
<td>ICC: mVel 0.71–0.75, Amp 0.36–0.37, area 0.55–0.62, MP 0.13–0.21, H 0.21–0.39</td>
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<tr>
<td>Kitabayashi et al., 2003 [36]</td>
<td>BP, narrow stance, EO/EC/F</td>
<td>34 parameters (e.g. area, mVel, RMS vel)</td>
<td>60</td>
<td>3</td>
<td>ICC (unclear)</td>
<td>ICC ≥ 0.70 all parameters, Vel most reliable: mVel AP/Ml, RMS vel: 0.96</td>
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<tr>
<td>Rogind et al., 2003 [35]</td>
<td>BP, EO/EC/F, normal/normal stance</td>
<td>Vel AP/Ml, 100% square, Max Ampl., sway index</td>
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<td>CV</td>
<td>CV: 0.13–0.23</td>
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<tr>
<td>Lafond et al., 2004 [25]</td>
<td>BP, 2 platforms Normal stance, EO/EC/F</td>
<td>RMS, range Vel, MPF, MPF/PO/Ml/MP/ML, area</td>
<td>120 (30, 60,120)</td>
<td>9</td>
<td>ICC ≥ 2</td>
<td>EO: mVel 2 trials 120s for ICC ≥ 0.90, RMS and range 6–8 trials 120s for ICC ≥ 0.90, mVel ML most reliable</td>
</tr>
<tr>
<td>Doyle et al., 2005 [13]</td>
<td>BP, EO/F, normal stance</td>
<td>FD, range, peak vel AP/Ml/TEA</td>
<td>10</td>
<td>3</td>
<td>ICC 3, TEM, CV</td>
<td>EO/EC/F AP/Ml: ICC FD &lt;0.75, range 0.43–0.71, Vmax 0.12–0.58, EO/EC/F AP/Ml: FD 0.62–0.90, range 0.28 to 0.72, Vmax 0.01–0.14.</td>
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<tr>
<td>Raymakers et al., 2005 [33]</td>
<td>BP, EO/F, narrow stance</td>
<td>Range, mVel, phase plane, area, DC</td>
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<td>2</td>
<td>CV (%)</td>
<td>CV: mVel 14, phase plane 18, area 26, DC 30, range AP 28, ML 19.</td>
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<td>BP, EO/F, stance unclear</td>
<td>Hurst exponent (SDA, DFA)</td>
<td>Up to 30</td>
<td>4</td>
<td>ICC ≥ 2</td>
<td>ICC increases with time (10 × 5 = 2.5 s), only DFA (elderly) 10 × ICC = 0.75</td>
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<td>Doyle et al., 2007 [39]</td>
<td>BP, EC/EO/F, normal stance</td>
<td>SD AP/Ml/Vel, Area</td>
<td>90 × 2</td>
<td>10</td>
<td>GC</td>
<td>GC higher with increased duration, mVel most reliable (0.64–0.95) EO/EC.</td>
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<td>Harringe et al., 2007 [41]</td>
<td>BP, EO/EC/F, normal stance</td>
<td>Path length, SD AP/Ml, RMS vel AP/Ml/Total, area</td>
<td>120</td>
<td>2</td>
<td>ICC ≥ 2, MMDC, CV</td>
<td>Healthy: ICC EO/F: 60s 0.34–0.66, 120s 0.40–0.78, EC/F: 60s 0.18–0.82, 120s 0.67–0.91, EO/C: 60s 0.14–0.73, 120s 0.47–0.90.</td>
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<td>Bauer et al., 2008 [11]</td>
<td>BP, EO/EC/F, narrow stance</td>
<td>Mean area, length, sway</td>
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<td>ICC 3</td>
<td>All parameters ICC &gt;0.75 except area EC (0.71)</td>
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<td>Demura et al., 2008 [29]</td>
<td>BP, EO/F, narrow stance</td>
<td>36 parameters (e.g. RMS, area, mVel, RMS Vel)</td>
<td>60</td>
<td>3</td>
<td>ICC (unclear)</td>
<td>All parameters ICC &gt;0.75 (e.g. mVel A: 0.96, B: 0.96, area A: 0.95, B: 0.92)</td>
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<tr>
<td>Doyle et al., 2008 [18]</td>
<td>BP, EO/EC/F normal stance</td>
<td>DC AP/Ml/short term/long term</td>
<td>30, 60, 90</td>
<td>10 × 2</td>
<td>GC</td>
<td>All parameters GC ≥ 0.70 after 2 trials 30s</td>
</tr>
<tr>
<td>Study</td>
<td>Condition</td>
<td>Parameters</td>
<td>Duration (s)</td>
<td>Repetitions</td>
<td>Statistics</td>
<td>Results</td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------------------------</td>
<td>---------------------------------</td>
<td>--------------</td>
<td>-------------</td>
<td>------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Haidan et al., 2008[40]</td>
<td>BP, EC/EO F/C, narrow stance</td>
<td>SD vel, ampl, phase plane</td>
<td>30</td>
<td>3</td>
<td>ICC</td>
<td>mVel EC/C 0.89, EC/F 0.87, EO/F 0.80. Area EC/C 0.65, EC/F 0.74, EO/F 0.10</td>
</tr>
<tr>
<td>Lin et al., 2008[16]</td>
<td>BP, EC/F, narrow stance</td>
<td>MPF, mVel, RMS, area, DFA exponent, Hurst exponent (H)</td>
<td>60</td>
<td>3</td>
<td>ICC</td>
<td>same day: ICC EC/C 0.75, EC/F 0.75, EO/F 0.50. inter-day: ICC EC/C 0.75, EC/F 0.75, EO/F 0.50</td>
</tr>
<tr>
<td>Elderly</td>
<td>All parameters ICC &gt; 0.75 same day</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santos et al., 2008[17]</td>
<td>BP, EO/EC/F, narrow stance</td>
<td>FD, mean freq/vel/dist, RMS</td>
<td>60</td>
<td>2</td>
<td>ICC</td>
<td>Vel AP/ML: EO 0.50–0.77, EC 0.71–0.83. Area range EO 0.52, EC 0.26. MPF EO 0.50, MPF EC 0.36</td>
</tr>
<tr>
<td>Salavati et al., 2009[27]</td>
<td>BP, EO/EC F/C, narrow stance</td>
<td>SD ampl/vel, phase plane</td>
<td>30</td>
<td>3</td>
<td>ICC</td>
<td>mVel EO 0.45, EC 0.36, range EO 0.10–0.20, EC 0.05–0.10. Area EO 0.63, EC 0.74</td>
</tr>
</tbody>
</table>

under the described conditions, only studies employing the same formulae can be directly compared with confidence. Results derived from similar or identical experimental setups may nevertheless offer a limited comparability. Trends like higher reliability with increasing trial numbers or under visual deprivation are present irrespective of the ICC model used, the overall conclusions therefore remain unaffected.

7.3. Subject demographics and morphology

While most articles provided basic details on the baseline demographics, only few articles addressed the effect of intrinsic physical differences between subjects such as body mass index (BMI), height or weight on the reliability of COP measures [23,24]. This should be included in all COP studies as it has been demonstrated that selected temporal-distance COP parameters such as mean velocity or range are strongly dependent on the subject’s height [23] and weight [25].

All but one of the studies reviewed relied on self-reported health information from the subjects without conducting some form of physical examination prior to the study. It remains questionable whether the participants in all cases remembered to report relevant previous injuries. Best practice would suggest conducting thorough physical examinations to rule out or identify biomechanical problems that may influence the readings.

A linear increase of COP velocity with increasing body weight, accounting for more than 50% of the observed variance, has also been demonstrated. As with increasing BMI (obesity) the centre of mass is located more anteriorly of the base of support and the foot mechanoreceptor afferents may be de-sensitized [25], the resulting postural instability may affect the reliability of COP measures. Another study argued that these effect are minimal when averaging at least three trials [24]. Until further evidence is established we nevertheless suggest normalizing the acquired data to these factors as originally described by O’Malley [26] and recently employed by Chiari et al. [23] and Pinsault and Vuillerme [27].

7.4. Age and gender

It is difficult to reach a conclusion regarding the effect of age and gender on the reliability of COP measures as only four studies offer direct comparability. Most studies enrolled mixed-gender groups which have shown high correlation coefficients [8]. In addition, even though it has been shown that COP measures differ between age groups [8,28,29], the reliability of these measures is not influenced by gender.

Demura et al. showed excellent reliability for a selection of different COP measures in both young and elderly subjects [29]. Lin et al., however, found higher inter-class correlation coefficients in groups of healthy elderly participants [14]. As discussed before, the higher ICCs reported in the elderly may be at least partially attributed to a higher variability of measures due to the expected age-related deficits in vision, proprioception or muscle strength.

The possible effect of fatigue, especially in a population of balance impaired or otherwise pathologically affected elderly subjects, has to be considered when increasing the trial number or duration on a single day. Finding the best ratio between trial duration and number of repetitions is of special interest. For example, it may prove impossible for such a group to perform multiple recordings of 180 s duration [10,30].

7.5. COP parameters

Recent studies suggest that the COP time series may represent the dynamics of a nonlinear (chaotic) system [31] that may be...
Satisfactory reliability (ICC, \(r = 0.75\)) motion of elderly subjects at 10 s duration could be assessed with a over three time intervals (2.5, 2 and 10 s) and showed that only AP Diffusion Analysis (SDA) and Detrended Fluctuation analysis (DFA) data. Amoud et al.\[32\] compared the reliability of Stabilogram which is surprising as previous research quoted in their own study sampling duration, while Doyle et al. recorded data for only 10 s, may be explained by the study design. Santos et al. used 60 s addition to different GC formulae, it is possible that the differences have comparable reliability values to traditional measures. In this conclusion. Their results show that fractal dimension data sets investigated. In a later study, Santos et al.\[17\] did not support conclusions described earlier have to be considered, it also shows later on, longer durations may have yielded higher reliability coefficients.

Traditional parameters that employ minimal, maximal or peak-to-peak readings such as maximal amplitude should be avoided as they use only one or two data points among the entire recorded data and are therefore subject to great variances with subsequent low reliability. As averaging data may decrease the extreme effects of individual extreme readings, COP summary measures such as COP mean velocity should be used instead. Considering the low number of participants throughout the available studies, extreme values will nevertheless influence these means, as the great spectrum of some confidence intervals suggest.

The data available shows that mean velocity (mVel) is one of the most commonly used COP parameters. While the overall limitations described earlier have to be considered, it also shows consistently acceptable reliability values (Table 3) and can be considered the most reliable traditional COP parameter.

The results of this review suggest that with sufficient repetitions and sampling duration, all COP parameters will gain acceptable reliability \(r > 0.75\). Depending on the specific research purpose, the selection should include both distance (e.g. area) as include that no instructions regarding the foot placement were given as well as the short sampling durations. As it will be shown later on, longer durations may have yielded higher reliability coefficients.


Commonly accepted interpretations of ICC and GC are \(-0.40 = 	ext{"poor"}, 0.40–0.75 = 	ext{"fair to good"}, >0.75 = 	ext{"excellent" reliability}\[15\].

### Table 3a

<table>
<thead>
<tr>
<th>Visual condition</th>
<th>Sampling frequency (Hz)</th>
<th>Cut-off frequency</th>
<th>Parameter</th>
<th>Number of trials</th>
<th>Duration (s)</th>
<th>Result</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes open (EO)</td>
<td>100</td>
<td>5</td>
<td>Mean velocity</td>
<td>3</td>
<td>50</td>
<td>GC 0.83</td>
<td>[39]</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>10</td>
<td>Mean velocity</td>
<td>3</td>
<td>50</td>
<td>ICC_2,1 0.89–0.95</td>
<td>[25]</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>10</td>
<td>Mean velocity</td>
<td>3</td>
<td>50</td>
<td>ICC_2,1 0.80</td>
<td>[40]</td>
</tr>
<tr>
<td>Eyes closed (EC)</td>
<td>64</td>
<td>Unclear</td>
<td>Mean velocity</td>
<td>3</td>
<td>50</td>
<td>ICC_2,1 0.84</td>
<td>[43]</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5</td>
<td>Mean velocity</td>
<td>3</td>
<td>50</td>
<td>GC 0.84</td>
<td>[39]</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>10</td>
<td>Mean velocity</td>
<td>3</td>
<td>50</td>
<td>ICC_2,1 0.87</td>
<td>[40]</td>
</tr>
</tbody>
</table>

Commonly accepted interpretations of ICC and GC are \(-0.40 = 	ext{"poor"}, 0.40–0.75 = 	ext{"fair to good"}, >0.75 = 	ext{"excellent" reliability}\[15\].

### Table 3b

<table>
<thead>
<tr>
<th>Duration (s)</th>
<th>Sampling frequency (Hz)</th>
<th>Cut-off frequency</th>
<th>Root mean square (RMS) AP/ML</th>
<th>Mean velocity</th>
<th>Area (A)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>20</td>
<td>10</td>
<td>EO/F ICC_2,1 0.35–0.39</td>
<td>EO/F ICC_2,1 0.73–0.87</td>
<td></td>
<td>[25]</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td></td>
<td>EO/F ICC_2,1 0.32–0.58</td>
<td></td>
<td></td>
<td>[17]</td>
</tr>
<tr>
<td>100</td>
<td>5</td>
<td></td>
<td>EO/F GC 0.64–0.93</td>
<td>EC/F GC 0.45–0.83</td>
<td></td>
<td>[39]</td>
</tr>
<tr>
<td>64</td>
<td>10</td>
<td></td>
<td>EO/F ICC_2,1 0.80</td>
<td>EC/F ICC_2,1 0.61–0.91</td>
<td>[43]</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>10</td>
<td></td>
<td>EO/F ICC_2,1 0.77–0.90</td>
<td></td>
<td></td>
<td>[25]</td>
</tr>
<tr>
<td>200</td>
<td>10</td>
<td></td>
<td>EO/F ICC_2,1 0.87</td>
<td></td>
<td></td>
<td>[40]</td>
</tr>
</tbody>
</table>

### Table 3c

<table>
<thead>
<tr>
<th>Number of repetitions</th>
<th>Study</th>
<th>Sampling frequency (Hz)</th>
<th>Cut-off frequency</th>
<th>Condition</th>
<th>Duration (s)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>43</td>
<td>64</td>
<td>Unclear</td>
<td>EC/F</td>
<td>5</td>
<td>mVel 0.82–0.83</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>100</td>
<td>5</td>
<td>EC/F</td>
<td>5</td>
<td>mVel 0.84–0.89</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>200</td>
<td>10</td>
<td>EC/F</td>
<td>5</td>
<td>mVel 0.87</td>
</tr>
</tbody>
</table>

Commonly accepted interpretations of ICC and GC are \(-0.40 = 	ext{"poor"}, 0.40–0.75 = 	ext{"fair to good"}, >0.75 = 	ext{"excellent" reliability}\[15\].

Characterized using fractal dimension \[13,19,30\] and Stabilogram Diffusion Analysis (SDA) \[30,32\]. SDA assumes that COP can be modeled as a system of correlated, random walks, thereby addressing the dynamic nature of COP motion, its analysis is based on the random selection of two pairs of COP data. Amoud et al.\[11\] noted that reliability coefficients for traditional measures such as mean velocity (mVel) or area were low (ICC_2,1 0.05–0.71) while fractal dimension showed high values (ICC_2,1 0.62–0.90) with low coefficients of variation (CV%) \(1.8–6.7\). It was therefore concluded that fractal analysis is a superior tool for COP investigations. In a later study, Santos et al.\[17\] did not support this conclusion. Their results show that fractal dimension data sets have comparable reliability values to traditional measures. In addition to different GC formulae, it is possible that the differences may be explained by the study design. Santos et al. used 60 s sampling duration, while Doyle et al. recorded data for only 10 s, which is surprising as previous research quoted in their own study \[22\] indicated that this is an insufficient time frame to gain reliable data. Amoud et al.\[32\] compared the reliability of Stabilogram Diffusion Analysis (SDA) and Detrended Fluctuation analysis (DFA) over three time intervals (2.5, 2 and 10 s) and showed that only AP motion of elderly subjects at 10 s duration could be assessed with a satisfactory reliability (ICC_1 ≥ 0.75). Limitations of their study.
well as time–distance (e.g. mVel) based parameters to gain a
diverse description of the COP excursion.

7.6. Experimental setup

About 28% [9,32] of the studies reviewed failed to state the instructions given to participants for the experiment. The two most commonly used instruction in the studies reviewed were “stand quietly” and “stand as still as possible”. In their study, Zok et al. [33] showed that the instructions issued to the participants during posturography may have a significant impact on the results. Most COP parameters investigated showed variations of 8–71% depending on which one of the instructions was given. Results obtained when the subjects were asked to “stand as still as possible” showed narrower confidence intervals indicating a higher consistency. We therefore recommend explicit instructions be given to participants in COP measurement studies. These instructions should be “stand as still as possible” while looking straight ahead.

Just a few studies reported some form of standardization of the environment such as lighting, temperature or time of day for the follow-ups [9,34]. Another potential limitation was varying foot positions when stepping off and back on the force platform during breaks. Only one study avoided this effect by having the participants sit down during breaks while maintaining the original foot position [35]. The arms at sides position was most commonly used position (60%). From a biomechanical point of view, this is more likely to keep the COP in a natural position than a position with hands in front or on the back. Accordingly, we recommend to remove shoes and have the arms at sides when data is being recorded.

7.7. Sampling and cut-off frequency

It has been shown that COP measures and its reliabilities vary depending on both the acquisition and cut-off frequency chosen [30,36]. In the literature, sampling frequencies ranging from 10 to 200 Hz have been reported [9,16,17,22,27,37–41] and it seems that the reported variations in COP reliability across similar experimental setups are at least partially due to the different frequencies chosen.

Filtering of any signal is aimed at the selective rejection, or attenuation, of certain frequencies. The effect on parameters defined on the basis of frequency distribution of data such as mean power frequency is marked, whereas measures of mean displacement such as mean velocity or mean amplitude are far less sensitive to different sampling frequencies [36]. It has been shown that COP mean displacement velocity and path length were 26.1% greater when sampling frequencies of 50 Hz were used compared to 10 Hz [30] as it would be expected with more data points describing the shape of the COP. This however, did not significantly affect reliability as mean velocity showed generally consistent reliabilities (r = 0.82–0.89) across different frequencies ranging from 64 to 200 Hz [27,38,39] (Table 3).

Depending on the parameter selected, the choice of the cut-off frequencies has a significant effect on the reliability of COP data. The results for mean velocity for example showed low variation from ICC2,1 = 0.75 at 0.8 Hz to 0.71 at 10 Hz, while the reliability values of mean power frequency dropped from 0.21 to 0.13 under the same condition. A cut-off frequency of 10 Hz has been suggested as the best compromise to reject noise power [36].

Depending on the COP parameter chosen, care should be taken with regards to the sampling frequency. Although further research is necessary, a sampling frequency of 100 Hz with a cut-off level of 10 Hz appears advisable for traditional COP measures.

7.8. Sampling duration

The test–retest results suggest that the number of trial recordings and duration appears to be a critical factor for obtaining reliable data sets. There have been few attempts to provide recommendations on both the length and number of trials that should be used when assessing balance. While earlier studies suggest that reliable data may be obtained with sample durations of 10–60 s [18,36,42,43]. This has later been disputed by studies investigating multiple time intervals of up to 120 s. They concluded that between 90 and 120 s are necessary to reach correlation coefficients of ≥0.75 for most COP parameters with confidence [15,22,38], further lengthening trial duration once an acceptable level is reached did not significantly reduce variability [9].

When similar studies are compared, the results confirm a trend towards increased reliability values with longer sampling durations. While the data presented includes only a limited selection of parameters from few studies and deriving from different statistical models, the values for mVel and RMS (AP/ML) show a positive relationship between sampling duration and reliability coefficient. This is also true for COP area, although the results for the different time intervals show a greater variation. Similar results can be observed with similar ICC models (Table 3).

Overall a sampling duration of 90 s can be expected to yield good reliability for all traditional COP parameters.

7.9. Number of repetitions

In addition to trial duration, the number of repetitions needed to gain acceptable reliability (r ≥ 0.75) also varies with the COP parameter under investigation and conflicting results have been reported. For COP mean velocity for example, just two 120 s trials were required to reach an ICC2,1 > 0.90, whereas COP range and RMS needed four 120 s trials to reach similar reliability levels [22]. Furthermore, it has been stated that averaging two [35], three [24], four [38] or seven [17] trials yields acceptable reliability for the majority of COP parameters.

When comparing results of similar setups, the trend for increased trial numbers to yield more reliable data is apparent (Table 3). In a clinical setting, however, it may be argued that setups involving 10 trials in elderly people are impractical. Given the heterogeneous study designs in this review we conclude that averaging 3–5 trials of sufficient duration over one day is appropriate under most conditions.

7.10. Visual condition

Loss of vision does not affect COP measures of a young population during quite standing, while the effect was more marked in the elderly [44]. Under eyes closed conditions the reliability is lower for short sampling durations and rises as the individual adapts [43], leading to higher overall reliability values under eyes closed condition compared to eyes open [8,9,11,17,22,37,38,40,45,46].

It has also been shown that while both conditions showed high reliability values, the overall eyes closed data was more reliable than eyes open even in elderly subjects [9]. This appears a bit surprising as postural stability in the eyes closed position would be expected to be harder to maintain due to the reduced effectiveness of peripheral proprioception with increasing age. While loss of vision leads to increased muscle stiffness [47], the higher variances of measures caused by the decreased postural stability under this visual condition would be expected to result in higher ICC values, as described earlier. In addition, the trend by recent papers to report higher reliability estimates under eyes closed conditions may at least partially be attributed to improved technical equipment, a more rigorous scientific procedures in
conducting the studies or a higher true score variability. For best practice we recommend that data be collected under eyes closed conditions.

7.11. Foot position

It has been shown that widening of the foot position increases the passive stability of the musculoskeletal system and decreases active neural control [23,48]. A wide foot position acts to strengthen the coupling between hips and ankles and would be expected to yield higher reliability coefficients under eyes closed conditions (especially in the elderly). Only one study by Hill et al. [41] directly compared narrow and normal stance. It showed that narrow stance measurements lead to lower overall reliability than feet apart (ICC2,1 = 0.27 compared to 0.55). The sampling duration, however, was short (25 s). Comparing selected data of similar studies indicates that while the correlation coefficients for seven repetitions after 60 s were significantly higher during normal stance (GC = 0.75) compared to narrow foot position (GC = 0.75) [17], both reached acceptable reliability. When data from a single 30 s trial were compared, narrow stance reached higher reliability values than a normal foot position [37] (Table 3).

No conclusion regarding the more reliable foot position can be reached with the current data available; accordingly best practice suggests that the position of the feet should be standardized. This may depend on the specific purpose of research and whether the participant’s physical condition allows for a more challenging position for the proprioceptive system or not.

7.12. Surface condition

Three studies investigated data obtained from both firm (F) and compliant surfaces (C). All of them enrolled subjects with various conditions ranging from vestibular impairment [19] and LBP to lower limb injuries [16,40]. Without testing with open eyes, Salavati et al. [24] reported lower ICC2,3 values with comparatively high standard error of measurement and coefficient of variation values for trials run on compliant surfaces with closed eyes. Benvenuti et al. [10] agree with this trend but added that the parameter COP distance antero-posterior tested on a compliant surface may be as reliable as on a firm base. This was the only study using elderly subjects (74.5 years), while the others enrolled young participants (14.9–38.4 years). In contrast, Harringue et al. [40] found generally lower correlation coefficients (ICC2,1) during eyes closed and open trials for both 60 and 120 s sampling duration on firm surface.

Even considering the differences in patient demographics and health condition, it may be concluded that data obtained on a firm surface tends to be more reliable, although no similar setups allow for a specific inter-study comparison of results. If the study purpose allows, we recommend using a firm surface although further research is required.

8. Conclusion

The overall results indicate that the reliability of traditional COP parameters is acceptable if our recommendations are followed in the study design. The test–retest reliability depends primarily on factors such as the number of trial recordings and duration rather than the selection of particular COP parameters. Care should be taken to thoroughly assess the subject’s physical status and anthropometric properties prior to the measurements. The primary finding of this systematic review is there is relatively little consistency in the methods employed and measurements selected for COP analysis when using a force–platform.

We recommend the following methods should be employed: regarding the data acquisition duration, the results suggest that a minimum of 90 s is required to reach acceptable reliability for all traditional COP parameters in healthy subjects. A sampling frequency of 100 Hz with a cut-off frequency of 10 Hz is advisable. In addition, measurements should be conducted under eyes closed condition on a firm surface. Averaging the results of three to five repetitions can be expected to yield reliable data. Although the specific effect on the reliability remains unclear, the current evidence suggests that “stand as still as possible” should be the instruction issued prior to the recording. No final recommendation regarding the foot position is possible at this point.

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Conflict of interest statement: The authors disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) this work.

References

Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: a systematic review of the literature

Alexander Ruhe · René Fejer · Bruce Walker

Abstract Over the past 20 years, the center of pressure (COP) has been commonly used as an index of postural stability in standing. While many studies investigated COP excursions in low back pain patients and healthy individuals, no comprehensive analysis of the reported differences in postural sway pattern exists. Six online databases were systematically searched followed by a manual search of the retrieved papers. The selection criteria comprised papers comparing COP measures derived from bipedal static task conditions on a force-plate of non-specific low back pain (NSLBP) sufferers to those of healthy controls. Sixteen papers met the inclusion criteria. Heterogeneity in study designs prevented pooling of the data so only a qualitative data analysis was conducted. The majority of the papers (14/16, 88%) concluded that NSLBP patients have increased COP mean velocity and overall excursion as compared to healthy individuals. This was statistically significant in the majority of studies (11/14, 79%). An increased sway in anteroposterior direction was also observed in NSLBP patients. Patients with NSLBP exhibit greater postural instability than healthy controls, signified by greater COP excursions and a higher mean velocity. While the decreased postural stability in NSLBP sufferers further appears to be associated with the presence of pain, it seems unrelated to the exact location and pain duration. No correlation between the pain intensity and the magnitude of COP excursions could be identified.

Keywords Balance · Center of pressure · Force-plate · Low back pain · Healthy controls · Systematic review

Background

Body sway can be assessed by measuring the deviations in the location of the center of pressure (COP) on the supporting surface by means of a force platform. COP refers to the point at which the pressure of the body over the soles of the feet would be if it were concentrated in one spot. It is, however, not a true record of body sway but rather a measure of the activity of the motor system in moving the COP. The cause of sway is attributed to many factors such as inherent noise within the human neuromotor system, as reflective of an active anticipatory search process, or as an output of a control process to maintain postural control [1–3]. Many uncontrollable factors may contribute to the degradation of the balance system such as decreased performance of the sensory-motor system with aging, neurological or musculoskeletal disorders such as low back pain (LBP) [4].

Low back pain is a common condition with a reported 1-year prevalence ranging from 22 to 65% [5]. While the majority of these cases resolve within 6 weeks without medical intervention [6], a minority of around 20% may progress to become chronic and constitute the western World’s most prevalent and costly health problem [7]. Recent evidence showed that while age is a major determinant for balance, low back pain might account for up to 9% of the variance in balance [8].
A variety of theories exists about the potential effect of NSLBP on postural stability. Ideally, the body should be able to generate quick COP transitions that just exceed the current position of the center of mass (COM) [3] and accelerate it into the opposite direction in order to maintain balance. On a basic level (chronic) damage of sensory tissues in the lumbar spine, trunk [9] or lower extremities [10] may affect postural stability. Deterioration of this proprioceptive information from these areas may be the determining factor in reducing the accuracy in the sensory integration process. The resulting imprecise estimation of the COM position especially in chronic LBP sufferers may then lead to an increase in the safety margin of the adaptive COP shifts with regard to the predicted COM oscillations [11].

Another possible mechanism behind balance alterations is acute “pain inhibition” [12]. In this case, discharge from high-threshold nociceptive afferents interferes with spinal motor-pathways [13] as well as the motor cortex [14]. In addition, it has been shown that pain may cause an increased presynaptic inhibition of muscle afferents [15] as well as affecting the central modulation of proprioceptive spindles of muscles [16], causing prolonged latencies by the decrease in muscle spindle feedback. These alterations may lead to decreased muscle control and result in increased postural sway.

This literature review will attempt to identify possible differences in COP pattern between NSLBP sufferers and healthy controls that may relate to the mechanisms described above. This step is fundamental before investigating whether a connection between the magnitude of these differences and the LBP intensity or location exists.

To our knowledge, no systematic review has been conducted to investigate the possible impact of low back pain on COP pattern and the possible association of this effect with pain intensity or disability.

Aims

The aims of this systematic literature review were: (1) to determine if there are significant differences in COP between LBP patients and healthy controls, (2) to investigate whether the magnitude of these COP excursions is related to the level of pain perception or (3) to the perceived level of disability.

Methods

Search strategy

A comprehensive search strategy was developed by identifying all potentially relevant search terms, categorizing these terms into specific search phases and subsequently combining them by using Boolean terms. This search strategy was applied to six different electronic databases: PubMed, MEDLINE, EMBASE, Web of Science, ScienceDirect, Digital Dissertations and the Cochrane library. The detailed search strategy will be made available upon contacting the corresponding author.

Electronic searches

All databases were searched using the search strategy described above. Appropriate minor modifications to the basic search template were made to optimize the strategy in each of the six databases. Papers were limited to human studies published between January 1980 and July 2009.

Searching other resources

The hand search included analyzing references cited in studies selected from the original online search. Citation searches of relevant studies were conducted using the PubMed, MEDLINE, and ScienceDirect databases.

Selection criteria

Papers were limited to peer-reviewed journals and dissertations without restrictions regarding language. Wide inclusion and exclusion criteria for study designs were in order to avoid limitation of potentially relevant papers.

The inclusion criteria were: papers in any language that were fully or partially concerned with COP measures of subjects with NSLBP derived from bipedal static tasks on a force-plate, compared to measures of healthy controls. For the purpose of this review, NSLBP was broadly defined as pain of musculoskeletal etiology in the absence of any neurological symptomatology or structural damage due to trauma or serious pathology such as cancer or infection.

All COP measures, experimental setups, and statistical models fitting these criteria were considered. No limitations of the type of patient demographics applied. We excluded studies with insufficient documentation of patient demographics or experimental setup where this rendered data extraction impossible. In addition, papers that were anecdotal, speculative, or editorial in nature or studies that employed dynamic task conditions such as one-leg hopping, walking, or some form of translation of the force platform were excluded.

Data extraction and management

For the purpose of this review, AR acted as the principal reviewer. A colleague was involved independently in the process of identifying relevant studies and did not participate in further analysis of the finally included papers.
About the research question, the data extraction con-
isted of five main areas regarding low back pain and
disability: (1) location and origin of the pain, (2) LBP
duration prior to the measurements, (3) number of previous
painful episodes, (4) perceived pain intensity, and (5) any
reported disability level.

For the purpose of this review, a $p$ value at or below
0.05 ($p \leq 0.05$) was considered statistically significant.

Assessment of methodology

Recently it was suggested that combined quality scores
should not be incorporated into systematic reviews and
instead the accuracy should be assessed by an investigation
into individual quality scores [17].

The reviewers specifically assessed the application,
documentation, and association of six individual items
concerning differences in COP measures between LBP
patients and healthy controls. The reviewed criteria for
experimental setups consisted of (1) subject demographics
and morphology, (2) sample duration, (3) number of trial
repetitions, (4) visual condition (eyes open or closed),
(5) stance, and (6) type of platform surface.

Results

Literature search results

Initially, the online search strategy identified 157 studies of
which the reviewers screened abstracts individually. The
application of inclusion/exclusion criteria and consensus by
the reviewers on the titles and abstracts eliminated a further
119 papers. The most common reason for rejection was not
meeting the selection criteria such as static or bipedal tasks.
From the titles and abstracts of papers selected ($n = 38$), full
papers were reviewed and the same two reviewers (AR and
TB) applied the inclusion criteria to the full text. Of these, 16
studies met the inclusion criteria and were included in this
review; 2 of these 16 were added after the hand search of
reference lists of included papers (Fig. 1).

Study results

Characteristics of participants and methods

There was no blinding of the examiners to the participant’s
health status described. Most authors described the baseline
demographics in appropriate detail by including weight,
height, age and gender (12/16, 75%), eight studies (50%)
included a physical examination in order to validate their
health status prior to study enrollment. Only one of the
included studies reported calibration procedures of the
force-plate [18], another one described procedures to
ensure that the participants resumed an identical foot
position throughout the trials [19].

Both subject demographics and health status for all
studies are shown in Table 1. With regard to patient
demographics, less than half of the included studies (41%)
enrolled mixed gender groups of healthy and NSLBP
participants. The studies employed rather broad age ranges
of participants, with the most commonly enrolled age range
being 21–40 years (76%).

While the majority of studies defined neurological
pathologies such as nerve root irritations in their exclusion
criteria, few studies specifically addressed excluding ves-
tibular conditions [21, 22, 26]. Other neurological condi-
tions affecting balance were not addressed. Only one study
investigated whether NSLBP sufferers were under the
influence of pain medication [14] and consequently
excluded those patients.

Table 2 shows the study characteristics and the results
of the most commonly used COP parameters. There is a
marked heterogeneity present in the in the included studies.
in terms of sample duration, number of trials or choice of COP parameters used. About 53% of the trials were performed under both eyes closed (EC) and eyes open (EO) conditions. Most of the authors conducted less than three repetitions of postural sway recordings (9/16, 56%). Mean velocity (mVel), mean distance/displacement, root mean square (RMS) as well as sway area accounted for most of the COP parameters selected (Table 2).

Although both height and weight have been shown to affect the reliability of COP measures [34, 35], none of the presented results was subject to a normalizing process for these factors. Normalizing refers to statistically removing the dependence of stabilometric parameters on biomechanical factors as originally proposed by Mok et al. [27].

**Reliability of COP data**

Table 3 gives an overview of how the studies included meet the ideal experimental setup for reliable data [36]. Generally, the most important factors for reliable data appear to be sampling duration, number of trials and visual condition. Irrespective of sampling frequency and cut-off frequency, a sufficient sampling duration (<90 s) in

### Table 1  Participant demographics and health status

<table>
<thead>
<tr>
<th>Study</th>
<th>Healthy status and number of participants</th>
<th>Gender</th>
<th>Age in years (SD)</th>
<th>Weight in kg (SD)</th>
<th>Height in cm (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Female</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Severe LBP: 31</td>
<td>18</td>
<td>20–60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Healthy: 61</td>
<td>29</td>
<td>20–60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mientjes and Frank [21]</td>
<td>LBP: 8</td>
<td>3</td>
<td>38.4</td>
<td>–</td>
<td>179</td>
</tr>
<tr>
<td></td>
<td>Healthy: 8</td>
<td>3</td>
<td>37.1</td>
<td>–</td>
<td>171</td>
</tr>
<tr>
<td>Kuukkanen and Malkia [22]</td>
<td>LBP: 90</td>
<td>–</td>
<td>39.9 (7.9)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Hamaoui et al. [23]</td>
<td>LBP: 10</td>
<td>0</td>
<td>33</td>
<td>77</td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>Healthy: 10</td>
<td>0</td>
<td>31</td>
<td>69</td>
<td>178</td>
</tr>
<tr>
<td>Grimstone and Hodges [24]</td>
<td>LBP: 10</td>
<td>–</td>
<td>32 (8.3)</td>
<td>69 (14.7)</td>
<td>173 (10.0)</td>
</tr>
<tr>
<td></td>
<td>Healthy: 10</td>
<td>–</td>
<td>26 (5.4)</td>
<td>66 (15.1)</td>
<td>171 (10.0)</td>
</tr>
<tr>
<td>Brumagne et al. [25]</td>
<td>LBP: 10</td>
<td>–</td>
<td>25</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Healthy: 10</td>
<td>–</td>
<td>25</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>LBP: 10</td>
<td>–</td>
<td>63</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Healthy: 10</td>
<td>–</td>
<td>63</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Hamaoui et al. [26]</td>
<td>LBP: 10</td>
<td>0</td>
<td>33</td>
<td>77</td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>Healthy: 10</td>
<td>0</td>
<td>31</td>
<td>69</td>
<td>178</td>
</tr>
<tr>
<td>Mok et al. [27]</td>
<td>LBP: 24</td>
<td>–</td>
<td>36.6 (10.0)</td>
<td>71.2 (11.5)</td>
<td>171 (9.0)</td>
</tr>
<tr>
<td></td>
<td>Healthy: 24</td>
<td>–</td>
<td>36.9 (10.5)</td>
<td>65.3 (11.6)</td>
<td>169 (8.0)</td>
</tr>
<tr>
<td>Smith et al. [28]</td>
<td>Healthy/induced LBP: 12</td>
<td>4</td>
<td>26 (4.0)</td>
<td>71 (12.0)</td>
<td>176 (12.0)</td>
</tr>
<tr>
<td>della Volpe et al. [2]</td>
<td>LBP: 12</td>
<td>5</td>
<td>35.4</td>
<td>–</td>
<td>174.9</td>
</tr>
<tr>
<td></td>
<td>Healthy: 12</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Popa et al. [29]</td>
<td>LBP: 13</td>
<td>6</td>
<td>35.1 (11.9)</td>
<td>76.5 (17.9)</td>
<td>174.3 (9.1)</td>
</tr>
<tr>
<td></td>
<td>Healthy: 13</td>
<td>–</td>
<td>32.2 (7.2)</td>
<td>69.5 (12.7)</td>
<td>174.4 (7.5)</td>
</tr>
<tr>
<td>Brumagne et al. [30]</td>
<td>LBP: 21</td>
<td>14</td>
<td>23.5 (1.0)</td>
<td>64.5 (12.9)</td>
<td>171.2 (10.2)</td>
</tr>
<tr>
<td></td>
<td>Healthy: 24</td>
<td>13</td>
<td>23.0 (1.6)</td>
<td>63.4 (10.1)</td>
<td>172.9 (9.5)</td>
</tr>
<tr>
<td>Lafond et al. [31]</td>
<td>LBP: 12</td>
<td>–</td>
<td>41.5</td>
<td>74.6</td>
<td>172.0</td>
</tr>
<tr>
<td></td>
<td>Healthy: 12</td>
<td>–</td>
<td>40.0</td>
<td>68.5</td>
<td>167.3</td>
</tr>
<tr>
<td>Harringe et al. [32]</td>
<td>LBP: 11</td>
<td>11</td>
<td>15.0</td>
<td>49.9</td>
<td>161</td>
</tr>
<tr>
<td></td>
<td>Healthy: 18</td>
<td>11</td>
<td>13.8</td>
<td>48.1</td>
<td>160</td>
</tr>
<tr>
<td>Mann et al. [19]</td>
<td>LBP: 10</td>
<td>10</td>
<td>57.6 (0.6)</td>
<td>57.6 (0.6)</td>
<td>165 (4.0)</td>
</tr>
<tr>
<td></td>
<td>Healthy: 10</td>
<td>10</td>
<td>20.27 (1.7)</td>
<td>56.7 (0.2)</td>
<td>166 (3.0)</td>
</tr>
<tr>
<td>Salavati et al. [33]</td>
<td>LBP: 22</td>
<td>9</td>
<td>26.1 (6.2)</td>
<td>67.1 (11.2)</td>
<td>172 (10.0)</td>
</tr>
<tr>
<td></td>
<td>Healthy: 22</td>
<td>9</td>
<td>25.0 (5.5)</td>
<td>66.5 (12.1)</td>
<td>173 (10.0)</td>
</tr>
</tbody>
</table>

*Low back pain*
<table>
<thead>
<tr>
<th>Study</th>
<th>Condition</th>
<th>Duration (s)</th>
<th>Number of trials</th>
<th>Parameter</th>
<th>Low back pain result (SD)</th>
<th>Healthy controls result (SD)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luoto et al. [20]</td>
<td>Normal stance, EO/F</td>
<td>25</td>
<td>1</td>
<td>mVel</td>
<td>Male:</td>
<td></td>
<td>&gt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A: 14 mm/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B: 13 mm/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Female:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A: 10 mm/s</td>
<td></td>
<td>&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B: 20 mm/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mientjes and Frank [21]</td>
<td>Normal stance, EO/EC, F/C</td>
<td>Unclear</td>
<td>3</td>
<td>mPos</td>
<td>–</td>
<td>–</td>
<td>0.099</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RMS (ML)</td>
<td>–</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RMS (AP)</td>
<td>–</td>
<td>0.031</td>
</tr>
<tr>
<td>Kuukkanen and Malkia [22]</td>
<td>Unclear stance, EC/F</td>
<td>20 (40)</td>
<td>1</td>
<td>mVel (AP)</td>
<td>17.1 mm (3.7)</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mVel (ML)</td>
<td>12.3 mm (2.7)</td>
<td>–</td>
</tr>
<tr>
<td>Hamaoui et al. [23]</td>
<td>Normal stance, EO/F</td>
<td>20</td>
<td>5</td>
<td>mPos (AP)</td>
<td>2.9 mm (0.5)</td>
<td>1.9 mm (0.8)</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mPos (ML)</td>
<td>1.6 mm (0.7)</td>
<td>1.1 mm (0.6)</td>
</tr>
<tr>
<td>Grimstone and Hodges [24]</td>
<td>Normal stance, EO/F</td>
<td>120</td>
<td>1</td>
<td>Mean displacement</td>
<td>3.2 mm</td>
<td>2.4 mm</td>
<td></td>
</tr>
<tr>
<td>Brumagne et al. [25]</td>
<td>Normal stance, Unclear visual condition/F</td>
<td>60</td>
<td>1</td>
<td>RMS (AP)</td>
<td>Young: ~8 mm</td>
<td>Young: ~5 mm</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Elderly: ~7.5 mm</td>
<td>Elderly: ~5 mm</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Hamaoui et al. [26]</td>
<td>Normal stance, EC/F</td>
<td>20</td>
<td>5</td>
<td>Mean displacement</td>
<td>AP 4.3 mm (1.6)</td>
<td>ML 2.0 mm (1.2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Narrow stance, EC/F</td>
<td></td>
<td></td>
<td></td>
<td>ML 1.3 mm (0.6)</td>
<td>AP 5.5 mm (1.5)</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ML 4.7 mm (1.6)</td>
<td></td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>Mok et al. [27]b</td>
<td>Normal stance, EC/F</td>
<td>70</td>
<td>1</td>
<td>mVel</td>
<td>4.3 mm (2.17)</td>
<td>5.03 mm (2.8)</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>Smith et al. [28]a</td>
<td>Normal stance, EC/EO/F</td>
<td>120</td>
<td>1</td>
<td>Mean displacement</td>
<td>EC: ~2.9 mm</td>
<td>EC: ~2.75 mm</td>
<td></td>
</tr>
<tr>
<td>della Volpe et al. [2]</td>
<td>Normal stance, EO/F</td>
<td>20</td>
<td>3</td>
<td>mVel (AP)</td>
<td>12.18 mm (1.2)</td>
<td>10.32 mm (0.6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RMS length</td>
<td>0.19 mm (0.01)</td>
<td>0.16 mm (0.01)</td>
</tr>
<tr>
<td>Popa et al. [29]</td>
<td>Normal stance, EC/F</td>
<td>20</td>
<td>3</td>
<td>Mean displacement</td>
<td>2.85 mm (0.024)</td>
<td>2.09 mm (0.01)</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Brumagne et al. [30]</td>
<td>Normal stance, EO/EC, F/C</td>
<td>60</td>
<td>1</td>
<td>RMS (AP)</td>
<td>EC/F: 8.8 mm</td>
<td>EC/F: 5.4 mm</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/F: 8.2 mm</td>
<td>EO/F: 6.2 mm</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: 7.5 mm</td>
<td>EC/C: 8.7 mm</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>Lafron et al. [31]a</td>
<td>Normal stance, EC/F</td>
<td>60</td>
<td>1</td>
<td>mVel (AP)</td>
<td>~5 mm/s</td>
<td>~3 mm/s</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td></td>
<td>Normal stance, EC/F</td>
<td>1,800</td>
<td>1</td>
<td>RMS length</td>
<td>~1.3 mm</td>
<td>~4.3 mm</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~8.0 cm^2</td>
<td>~4.7 cm^2</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mVel (AP)</td>
<td>~13.5 mm/s</td>
<td>~17.5 mm/s</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>RMS length</td>
<td>~11 mm</td>
<td>~17.5 mm</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Area</td>
<td>~18.5 cm^2</td>
<td>~25.0 cm^2</td>
</tr>
<tr>
<td>Harringe et al. [32]</td>
<td>Normal stance, EC/F</td>
<td>120</td>
<td>2</td>
<td>RMS Vel</td>
<td>2.2 mm/s (0.59)</td>
<td>2.06 mm/s (0.6)</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Area</td>
<td>7.11 cm^2 (3.04)</td>
<td>6.92 cm^2 (3.91)</td>
</tr>
<tr>
<td>Mann et al. [19]a</td>
<td>Normal stance, EC/F</td>
<td>30</td>
<td>1–3</td>
<td>SD vel</td>
<td>~6.7 mm/s</td>
<td>~5 mm/s</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>m displ AP</td>
<td>~7.6 mm</td>
<td>~3.3 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>m displ ML</td>
<td>~4.5 mm</td>
<td>~1.7 mm</td>
</tr>
<tr>
<td>Salavati et al. [33]</td>
<td>Normal stance, EC/F</td>
<td>30</td>
<td>3</td>
<td>SD vel</td>
<td>AP: 13.0 mm/s</td>
<td>AP: 14.8 mm/s</td>
<td>–</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>mVel</td>
<td>ML: 15.2 mm/s</td>
<td>–</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ML: 17.2 mm/s</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>13.7 mm/s (0.35)</td>
<td>15.9 mm (0.33)</td>
</tr>
</tbody>
</table>

*AP anteroposterior, BP bipedal, C compliant surface, displ displacement, EC eyes closed, EO eyes open, F firm surface, m displ mean displacement; ML medial–lateral, mPos mean position, mVel mean velocity, RMS root mean square, SD vel standard deviation of velocity

a The results presented have been extracted from bar-charts

b The results from unilateral and bilateral static task conditions were not differentiated
combination with the appropriate number of recordings (3–5) showed to yield reliable data for most COP parameters such as mean velocity (mVel) or area [32, 36, 37]. With few exceptions [2, 20, 23, 31], most of the studies conducted the trials under visual deprivation while only four [24, 28, 32, 38] applied a sampling duration that has shown sufficient reliability [36]. A minority used three or more trial repetitions [2, 19, 21, 26, 29, 33].

Pain characteristics

Only half the studies (8/16, 50%) stated the total low back pain duration prior to the test (ranging from 1 to 10.5 years); the long-term implications of this factor on COP excursions cannot be assessed. Of all the studies only, a minority (6/16, 38%) correlated this duration to pain intensity (Table 4).

Pain assessment

Due to the described heterogeneity in the experimental setups, a direct comparison of data sets is problematic. Only about half of the studies described some form of physical examination prior to the recordings (9/16, 57%). While all investigated the effect of NSLBP on COP measures, not all studies (9/16, 57%) assessed the pain level in some form e.g., by means of a visual analogue scale (VAS). Luoto et al. [20] mentioned collecting VAS data of their participants but this data is missing in the published paper.

The participants of two studies did not experience any pain at the time of recording [24, 33, 39], neither did four individuals of another [32]. While Brumagne et al. [30] stated that their participants were not in an acute recurrence of NSLBP; they nevertheless reported VAS scores of 2.2 ± 1.5 and were consequently counted as in pain. The perceived pain levels were similar throughout the studies at around 2.5 (VAS), indicating mild-to-moderate pain (Table 4).

Low back pain and postural sway

Generally, there is a great variability in the reported COP measures irrespective of the parameter chosen. The results of the included studies indicate that patients suffering from NSLBP exhibited a greater postural instability than healthy controls. This difference was statistically significant in the majority of studies (14/16, 88%). Only two studies found significantly lesser COP excursions in patients suffering from low back pain [27, 33].

Compared to healthy controls, participants with NSLBP exhibited a greater sway area [31, 32], which varied greatly between 7.11 [32] and 18.5 cm² [31]. The NSLBP patients also showed an increased COP mean displacement [23, 24, 26, 28, 29]. This difference was significant in the AP direction [23, 26, 29]. The general trend towards an increased AP sway in pain sufferers was also present when considering the root mean square (RMS) for anteroposterior sway [30, 40], an effect that was found to increase with longer sampling durations [31].

---

**Table 3 Reliability criteria**

<table>
<thead>
<tr>
<th>Study</th>
<th>Sampling frequency</th>
<th>Cut-off frequency</th>
<th>Duration</th>
<th>Number of repetitions</th>
<th>Visual condition</th>
<th>Surface Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended</td>
<td>~100 Hz</td>
<td>10 Hz</td>
<td>≥90 s</td>
<td>3–5</td>
<td>Eyes closed</td>
<td>Firm</td>
</tr>
<tr>
<td>Luoto et al. [20]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Mientjes and Frank [21]</td>
<td>0</td>
<td>0</td>
<td>Unclear</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Kuukkanen and Malkia [22]</td>
<td>Unclear</td>
<td>Unclear</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Hamaoui et al. [23]</td>
<td>0</td>
<td>Unclear</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Grimstone and Hodges [24]</td>
<td>Unclear</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Brumagne et al. [25]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Unclear</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Hamaoui et al. [26]</td>
<td>Unclear</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Mok et al. [27]</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+ +++</td>
</tr>
<tr>
<td>Smith et al. [28]</td>
<td>+</td>
<td>Unclear</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++++</td>
</tr>
<tr>
<td>della Volpe et al. [2]</td>
<td>Unclear</td>
<td>Unclear</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Popa et al. [29]</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Brumagne et al. [30]</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Lafond et al. [31]</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Harringe et al. [32]</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Mann et al. [19]</td>
<td>+</td>
<td>Unclear</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Salavati et al. [33]</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++++</td>
</tr>
</tbody>
</table>
Additionally, a higher COP sway velocity was found in non-specific LBP cases [2, 19, 20, 31, 32]. The mean velocities ranged from about 2.23 [32] to 17.1 mm/s [22] throughout the studies. For comparison, Table 5 shows the results for the parameter mean velocity.

The contribution of visual information

The results show that the differences in COP pattern between LBP sufferers and healthy controls gain significance under visual deprivation. An increase in postural sway in the absence of visual input has been observed by numerous studies of healthy participants [19, 22, 29, 41]. In a study enrolling patients suffering from lumbar disc pathologies, the level of significance between those and healthy controls increased from *p < 0.05 ( 12 mm/s compared to *p < 0.01 ( 23 and ~ 13 mm/s, respectively) under eyes closed condition for COP mean velocity [41]. Mann et al. [19] reported that the presence of visual input did not influence COP mean velocity in healthy subjects and no difference between healthy controls and LBP patients was observed under eyes open.

### Table 4 Pain definition, intensity and characteristics of included studies

<table>
<thead>
<tr>
<th>Study</th>
<th>Physical examination</th>
<th>Low back pain</th>
<th>Pain presence in years (SD)</th>
<th>Pain present at time of trial (n)</th>
<th>Pain intensity evaluation (pre-trial)</th>
<th>Score (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luoto et al. [20]</td>
<td>Yes</td>
<td>Chronic</td>
<td>–</td>
<td>Yes (99/99)</td>
<td>VAS</td>
<td>Unclear</td>
</tr>
<tr>
<td>Mientjes and Frank [21]</td>
<td>–</td>
<td>Chronic</td>
<td>10.9</td>
<td>Yes (8/8)</td>
<td>VAS</td>
<td>2.6</td>
</tr>
<tr>
<td>Kuukkanen and Malkia [22]</td>
<td>Yes</td>
<td>Subacute</td>
<td>10 (8.4)</td>
<td>Yes (58/58)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Hamaoui et al. [23]</td>
<td>–</td>
<td>Chronic</td>
<td>–</td>
<td>Yes (10/10)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Grimstone and Hodges [24]</td>
<td>–</td>
<td>Chronic</td>
<td>3.54</td>
<td>Yes (10/10)</td>
<td>VAS</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Brumagne et al. [25]</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Unclear</td>
<td>–</td>
</tr>
<tr>
<td>Hamaoui et al. [26]</td>
<td>Yes</td>
<td>Chronic</td>
<td>–</td>
<td>Yes (10/10)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mok et al. [27]</td>
<td>–</td>
<td>Chronic</td>
<td>10.5 (8)</td>
<td>Yes (24/24)</td>
<td>VAS</td>
<td>2.0 (1.6)</td>
</tr>
<tr>
<td>Smith et al. [28]</td>
<td>–</td>
<td>Acute</td>
<td>–</td>
<td>Yes (12/12)</td>
<td>VAS</td>
<td>4.4 (1.9)</td>
</tr>
<tr>
<td>della Volpe et al. [2]</td>
<td>Yes</td>
<td>Chronic</td>
<td>5.2</td>
<td>Yes (12/12)</td>
<td>NRS-11</td>
<td>2–5/10</td>
</tr>
<tr>
<td>Popa et al. [29]</td>
<td>Yes</td>
<td>Chronic</td>
<td>5.2 (3.3)</td>
<td>Yes (13/13)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Brumagne et al. [30]</td>
<td>–</td>
<td>Chronic</td>
<td>3.4 (2.5)</td>
<td>Yes (21/21)</td>
<td>VAS</td>
<td>2.2 (1.5)</td>
</tr>
<tr>
<td>Lafond et al. [31]</td>
<td>Yes</td>
<td>Chronic</td>
<td>–</td>
<td>Yes (10/10)</td>
<td>VAS</td>
<td>2.5</td>
</tr>
<tr>
<td>Harringe et al. [32]</td>
<td>–</td>
<td>–</td>
<td>Mostly (7/11)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mann et al. [19]</td>
<td>Yes</td>
<td>Chronic</td>
<td>–</td>
<td>Yes (10/10)</td>
<td>VAS</td>
<td>6 (2)</td>
</tr>
<tr>
<td>Salavati et al. [33]</td>
<td>–</td>
<td>Episodic</td>
<td>1.0</td>
<td>No (22/22)</td>
<td>VAS</td>
<td>&lt;2.0</td>
</tr>
</tbody>
</table>

Visual analogue scale (VAS) ranging 0–10, 0–2 light pain; 3–5 light-to-moderate pain; 6–7 moderate-to-intense pain; 8–10 unbearable pain

a Chronic pain is defined as pain presence for at least 3 months

### Table 5 The effect of NSLBP on postural sway for the COP parameter mean velocity (mVel)

<table>
<thead>
<tr>
<th>Study</th>
<th>Duration (s)</th>
<th>Number of trials</th>
<th>Healthy controls Result (SD)</th>
<th>LBP patients (SD)</th>
<th>Pain severity (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luoto et al. [20]</td>
<td>15</td>
<td>1</td>
<td>Male: 12 mm/s</td>
<td>Male: 14 mm/s</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1</td>
<td>Female: 11 mm/s</td>
<td>Female: 10 mm/s</td>
<td>Moderate</td>
</tr>
<tr>
<td>della Volpe et al. [2]</td>
<td>20</td>
<td>3</td>
<td>AP: 12.2 mm/s (1.2)</td>
<td>AP: 10.3 mm/s (0.6)</td>
<td>2–5 NRS-11</td>
</tr>
<tr>
<td>Lafond et al. [31]</td>
<td>60</td>
<td>1</td>
<td>~ 3 mm/s</td>
<td>~ 5 mm/s</td>
<td>2.5 VAS</td>
</tr>
<tr>
<td>Mann et al. [19]a</td>
<td>30</td>
<td>1–3</td>
<td>~ 5 mm/s</td>
<td>~ 6.7 mm/s</td>
<td>6 (2) VAS</td>
</tr>
<tr>
<td>Salavati et al. [33]a</td>
<td>30</td>
<td>3</td>
<td>15.9 mm/s (0.33)</td>
<td>13.7 mm/s (0.35)</td>
<td>&lt;2.0 VAS</td>
</tr>
</tbody>
</table>

Visual analogue scale (VAS) ranging 0–10, 0–2 light pain; 3–5 light-to-moderate pain; 6–7 moderate-to-intense pain; 8–10 unbearable pain
NRS-11 ranging from 0 “no pain” to 10 “worst possible pain”
a The results presented have been extracted from bar-charts
condition. With closed eyes, however, a significant difference became apparent (5 mm/s compared to 6.7 mm/s, \( p = 0.015 \)).

Sampling duration

Most studies focused on investigating COP excursions of NSLBP sufferers during relatively short sampling durations of up to 120 s, observing the described increased postural instability. Only one study assessed body sway during prolonged standing of 30 min [31].

Disability assessment

The study designs and variable health characteristics of the participants render any direct comparison of results problematic (Table 6). The majority of the included studies (12/16, 75%) investigated the perceived level of disability of the participants. Two of the papers [20, 22] failed to document the results; another one only assessed post-trial disability levels [21]. In addition to the Roland and Morris [42] questionnaire, the Oswestry [43] questionnaire was the most commonly used (8/12, 67%). The scores generally show great variability ranging 1–32/50 (Oswestry) and 3.2–17/24 (Roland–Morris).

Discussion

Due to the heterogeneous study designs and experimental setups, pooling of data was not possible. However, despite the great variability across the included studies our systematic review showed that patients suffering from NSLBP exhibit a significantly increased COP sway. Unfortunately, the magnitude of these differences in postural sway cannot be summarily expressed in terms of specific percentages or values. As a result, only a general trend is noted.

The reliability of COP measurements is determined by factors such as sampling duration, sampling frequency and number of trials [36]. In our critical review, only about half the included studies fulfilled three or more of these recommended reliability criteria. However, there was a trend towards better methodological reporting in the more recent studies. Despite this fact, it is worth bearing in mind that studies with less than all six criteria may still present fairly reliable results.

About vision, an increase in COP excursions has been observed under visual deprivation as compared to EO patients suffering from NSLBP. This supports the previously mentioned proprioceptive deficits in NSLBP patients. An existing impaired sensory input from muscles and joints is more severely challenged with closed eyes. Vision is primarily used in controlling low frequency disturbances [44], as occurring during quiet stance. In conjunction with vestibular information, it is essential for stabilizing upright posture. In patients with a reduction in proprioceptive input, as seen in chronic NSLBP, it is therefore common to find a greater reliance on visual and vestibular cues to maintain postural stability. Visual obstruction will therefore exhibit a profound effect on balance as the system is deprived of two major contributors for postural control.

Table 6 Disability definition and characteristics of included studies

<table>
<thead>
<tr>
<th>Study</th>
<th>Disability assessed</th>
<th>Questionnaire</th>
<th>Score (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luoto et al. [20]</td>
<td>Yes</td>
<td>Oswestry</td>
<td>Unclear</td>
</tr>
<tr>
<td>Mientjes and Frank [21]</td>
<td>Yes</td>
<td>Oswestry (post-trial)</td>
<td>9–32/50 (mean 15.6)</td>
</tr>
<tr>
<td>Hamaoui and Malkia [22]</td>
<td>No</td>
<td>Oswestry</td>
<td>Unclear</td>
</tr>
<tr>
<td>Hamaoui et al. [23]</td>
<td>No</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Grimstone and Hodges [24]</td>
<td>No</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Brumagne et al. [25]</td>
<td>Yes</td>
<td>Oswestry</td>
<td>20/50</td>
</tr>
<tr>
<td>Hamaoui et al. [26]</td>
<td>No</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mok et al. [27]</td>
<td>Yes</td>
<td>Roland–Morris</td>
<td>3.2 (3.5)/24</td>
</tr>
<tr>
<td>Smith et al. [28]</td>
<td>No</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>della Volpe et al. [2]</td>
<td>Yes</td>
<td>Oswestry</td>
<td>1–24/50 (mean 7.8)</td>
</tr>
<tr>
<td>Popa et al. [29]</td>
<td>Yes</td>
<td>Oswestry</td>
<td>0–24/50 (mean 7.08)</td>
</tr>
<tr>
<td>Brumagne et al. [30]</td>
<td>Yes</td>
<td>Oswestry</td>
<td>7.3 (7.6)/100</td>
</tr>
<tr>
<td>Lafond et al. [31]</td>
<td>Yes</td>
<td>Oswestry</td>
<td>12.6/50 (7.3)</td>
</tr>
<tr>
<td>della Volpe et al. [2]</td>
<td>Yes</td>
<td>Oswestry</td>
<td>12.6/50 (7.3)</td>
</tr>
<tr>
<td>FABQ</td>
<td>No</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mann et al. [19]</td>
<td>No</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Salavati et al. [33]</td>
<td>Yes</td>
<td>Roland–Morris</td>
<td>3.4/24 (3.2)</td>
</tr>
</tbody>
</table>
The pronounced anteroposterior sway with the resulting raised ankle stiffness [11] observed in NSLBP sufferers [23, 26, 29] may be seen as a compensatory mechanism to enhance sensory discrimination and thereby compensate for the deterioration of the feedback loop [29].

Interestingly, the magnitude of COP excursions varies depending on the location of the pain. Experimentally induced pain into the biceps muscle, for example, did not exhibit any significant effect on postural sway [2], while a similar injection of levo-ascorbic acid (L-AS) into the feet elicited the same basic COP pattern found in chronic LBP sufferers. As the pain level was increased, so did the COP mean velocity and range in anterior–posterior direction [45].

Clinical application of COP measures

While this literature review shows that statistically significant differences in postural sway are present, the clinical application of COP measurements still remains limited for five major reasons described below.

Firstly, the causative factor for the altered postural sway is still unknown. The question remains whether the increased COP excursions are related to the previously described physiological changes due to chronic pain perception or rather acute “pain inhibition” [12]. If the latter mechanism is mainly responsible, monitoring NSLBP sufferers during their treatment and rehabilitation process may aid as an objective tool in assessing the patient’s progress. If long-term neurophysiological changes are primarily involved, individually varying recovery time frames may render such measurements less useful.

Secondly, the data available is insufficient to determine whether some form of linear or non-linear correlation between the perceived pain intensity and the magnitude of postural sway exists. At similar VAS scores, the reported results for COP mean velocity vary considerably. While one study reported a 100% increase in sway velocity with increasing pain perception [20], other studies showed no significant difference [19, 31].

Thirdly, the effect of pain duration, episodes of LBP and disability on COP excursions remain unclear. Due to the heterogeneous patient groups with a wide variety of pain durations and no information on the number of previous painful episodes being available, no conclusions can be drawn. Another contributing factor may be that self-reporting of LBP is prone to recall bias [46] and the definitions of NSLBP contained some variation throughout the studies. Both Oswestry and Roland–Morris results showed equally great variability which, in addition to the heterogeneous experimental setups, prevents interpretation. Further research is necessary to answer this question.

Fourthly, it has been shown that there is a steady natural increase in COP excursions with aging [47]. The rather broad age range of participants throughout the studies prevents an analysis of whether this also applies to pain-induced postural instability and how this magnitude correlates to specific age groups.

Finally, “normal” values are largely unknown and only one large-scale study offers reference values of healthy individuals for various COP parameters [47]. Similarly, reference data needs to be established for different LBP subgroups as a foundation for any intervention study. Until then, the identification of different COP patterns may be considered of academic rather than of clinical value at this time.

Conclusion

Patients with non-specific LBP exhibit greater postural instability than healthy controls. This difference is more pronounced under visual obstruction and can be attributed to either acute pain inhibition or diminished proprioceptive input from the lumbar spine and trunk muscles due to long-term neurological adaptations.

The decreased postural stability in NSLBP sufferers further appears to be associated with the acute presence of pain. There is insufficient data to suggest a relationship between pain intensity, previous pain duration or the level of perceived disability and the magnitude of COP excursions.

The clinical application of COP measures is limited by the unknown origin of the altered sway pattern, as well as a lack of COP reference values for different gender and age groups under both healthy and NSLBP. Further research is necessary to address these issues.

Limitations

A limitation of this literature review is the search strategy and its limitation to six databases, which might not have identified all relevant papers. To overcome this, a dynamic search strategy was employed with selected hand searches of reference lists. Another limitation is the fact that only very few papers allowed for any direct inter-study comparison of results and many conclusions had to be drawn from those studies.
Acknowledgments The author(s) like to thank Tino Bos (TB) for his valuable contribution during the first phase of the literature search.

Conflict of interest The author(s) declare that they have no competing interests. No funding was received for this review.

References


Altered postural sway in patients suffering from non-specific neck pain and whiplash associated disorder - A systematic review of the literature

Alexander Ruhe1*, René Fejer2 and Bruce Walker3

Abstract

Study design: Systematic literature review.

Objectives: To assess differences in center of pressure (COP) measures in patients suffering from non-specific neck pain (NSNP) or whiplash-associated disorder (WAD) compared to healthy controls and any relationship between changes in postural sway and the presence of pain, its intensity, previous pain duration and the perceived level of disability.

Summary of Background data: Over the past 20 years, the center of pressure (COP) has been commonly used as an index of postural stability in standing. While several studies investigated COP excursions in neck pain and WAD patients and compared these to healthy individuals, no comprehensive analysis of the reported differences in postural sway pattern exists.

Search methods: Six online databases were systematically searched followed by a manual search of the retrieved papers.

Selection Criteria: Papers comparing COP measures derived from bipedal static task conditions on a force plate of people with NSNP and WAD to those of healthy controls.

Data collection and analysis: Two reviewers independently screened titles and abstracts for relevance. Screening for final inclusion, data extraction and quality assessment were carried out with a third reviewer to reconcile differences.

Results: Ten papers met the inclusion criteria. Heterogeneity in study designs prevented pooling of the data and no direct comparison of data across the studies was possible. Instead, a qualitative data analysis was conducted. There was broad consensus that patients with either type of neck pain have increased COP excursions compared to healthy individuals, a difference that was more pronounced in people with WAD. An increased sway in antero-posterior direction was observed in both groups.

Conclusions: Patients with neck pain (due to either NSNP or WAD) exhibit greater postural instability than healthy controls, signified by greater COP excursions irrespective of the COP parameter chosen. Further, the decreased postural stability in people with neck pain appears to be associated with the presence of pain and correlates with the extent of proprioceptive impairment, but appears unrelated to pain duration.

Keywords: Balance, center of pressure, force-plate, neck pain, whiplash, systematic review

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Background

Rationale

Ideally, the body should be able to generate quick center of pressure (COP) transitions that just exceed the current position of the center of mass (COM) [1] and accelerate it into the opposite direction in order to maintain balance. Any condition affecting the afferent sensory pathways may interfere with this process. The neck is particularly prone to this due to the abundant cervical sensory receptors in joints and muscles [2,3] as well as their central and reflex connections to visual, vestibular and postural control systems [4].

The debate continues however, as to whether the cause of abnormal cervical afferent input is primarily proprioceptive or nociceptive in nature. Deterioration of this proprioceptive information from the neck may be the determining factor in reducing the accuracy in the sensory integration process. The resulting imprecise estimation of the COM position may then lead to an increase in the safety margin of the adaptive COP shifts with regard to the predicted COM oscillations [5].

The excitation of chemosensitive nociceptors in cervical facet joints and muscles may alter the sensitivity of the muscle spindles by reflex activation of fusimotor neurones [6], leading to a decreased proprioceptive acuity. This effect may be triggered by marked activation of mechanosensitive nociceptors as occurs in whiplash injuries [7]. Acute “pain inhibition” [8] may be another mechanism where discharge from high-threshold nociceptive afferents interferes with spinal motor-pathways as well as the motor cortex. Pain may also cause an increased pre-synaptic inhibition of muscle afferents [9] as well as affect the central modulation of proprioceptive spindles of muscles [10], causing prolonged latencies. Such alterations may lead to decreased muscle control and result in increased postural sway.

In the case of whiplash associated disorder (WAD), facet joint components may be at risk of injury due to compression during rear-impact accelerations while capsular ligaments are at risk of injury at higher accelerations [11]. Depending on the magnitude of trauma, the resulting impairment of the sensory system is therefore likely to be more pronounced compared to cases of non-specific neck pain (NSNP).

Several attempts have been made to investigate differences in COP sway pattern between people with NSNP and healthy controls by means of forceplate tilting [12], body leaning [13] or vibratory stimulation to structures of the neck [14]. Although these approaches contribute important knowledge to the field, an experimental setup without additional equipment for stimulation or external perturbation that can be applied comprehensively for a broad spectrum of complaints may be of additional use.

We previously described that such a simple static setup is not only highly discriminative for non-specific low back pain [15] but also allowed the observation of a linear relationship between the perceived pain intensity and COP sway velocity [16]. If people with NSNP can also be identified by COP measurements during such basic postural tasks, similar relationships are likely and may allow for comparison of postural sway between painful regions.

This literature review will attempt to identify possible differences in COP pattern between people with WAD, people with NSNP and healthy controls that may relate to the mechanisms described above. As COP measures are commonly used in a clinical setting, this will allow the researcher or clinician to put their results into context. To our knowledge no comprehensive systematic review has been conducted to investigate the possible impact of neck pain on COP pattern during bipedal static tasks and the possible association of this effect with pain intensity or disability.

Objective

The objective of this systematic literature review is to 1) determine if there are significant differences in postural sway between people with NSNP and WAD patients and healthy controls, 2) investigate whether the magnitude of these COP excursions are related to the level of pain perception, previous pain duration or perceived level of disability.

Methods

Search

A comprehensive search strategy was developed by identifying all potentially relevant search terms, categorizing these terms into specific search phases and subsequently combining them by using Boolean terms. This search strategy was applied to six different electronic databases: PubMed, MEDLINE, EMBASE, Web of Science, ScienceDirect and the Cochrane library. The date range of publications searched was from January 1980 to January 2011.

The following key words were used in the search strategy: “neck pain”, “cervical pain”, “whiplash”, “WAD”, “center of pressure”, “COP”, “balance”, “posture”, “postural stability”, postural control”. The detailed search strategy is available upon contacting the corresponding author.

The hand search included analyzing references cited in studies selected from the original online search. Citation searches of relevant studies were conducted using the PubMed, MEDLINE and ScienceDirect databases.

Eligibility criteria

Papers were limited to those published in peer-reviewed journals without language restrictions.
The inclusion criteria were: the study investigated force changes over time (postural sway) exhibited by participants with NSNP or WAD derived from bipedal static task conditions on a forceplate, ideally compared to measures of healthy controls. For the purpose of this review, NSNP was broadly defined as pain in the cervical area of musculoskeletal origin in the absence of any neurological symptomatology or serious pathology such as cancer or infection. Induced neck pain in otherwise healthy participants is considered as non-specific neck pain.

The selection criteria for this review does not concern study type as the focus is comparing COP sway data irrespective of the original research purpose of the study. Further, the quality of the various postural sway measures depends on technical aspects of the experimental setup. Therefore all study designs were considered.

We excluded studies with insufficient documentation of patient demographics or experimental setup where this rendered data extraction impossible. In addition, papers that were anecdotal, speculative or editorial in nature or studies that employed dynamic task conditions such as one-leg hopping, walking or some form of translation of the force platform were excluded.

**Information sources**

**Study selection**

For the purpose of this review AR acted as the principal reviewer. A colleague (TB) was involved independently in the process of identifying relevant studies but did not participate in further analysis of the finally included papers. Where discrepancies between AR and TB were not reconciled by discussion, a third reviewer was used for a majority decision.

**Data collection process**

To standardize the procedure between the reviewers, the main author developed a detailed data extraction sheet to acquire general information on objectives, design, participant’s demographics and outcomes. If any title and abstract did not provide enough information to decide whether or not the inclusion criteria were met, the article was included for the full text selection.

With regard to the research question, data extraction was concerned with four main areas regarding the association between neck pain and postural sway: 1) perceived pain intensity, 2) previous pain duration, 3) reported disability levels and 4) the experimental setup applied.

For the latter, we extracted data on 1) sampling duration, 2) number of trials, 3) sampling and cut-off frequency, 4) foot position, 5) visual condition (eyes open/closed), 6) surface condition (firm/compliant) as well as 7) the COP parameters used. These points were based on recommendations for obtaining reliable COP measures [17].

**Summary measures**

The principle summary measure in the included studies was differences in means.

**Synthesis of results**

We planned to combine the results of the included studies to conduct inter-study comparisons of means and statistical differences. We also planned to do this for NSNP and WAD separately and combined to investigate differences between the two.

**Results**

**Study selection**

Initially, the database search strategy identified 203 studies of which titles and abstracts were screened individually by the reviewers. The application of inclusion/exclusion criteria and consensus by the reviewers on the titles and abstracts eliminated 182 papers. From the titles and abstracts of papers selected (n = 23), full papers were reviewed by the same two reviewers (AR and TB) who applied the inclusion criteria to the full text. Of these, 10 studies met the inclusion criteria and were included in this review (Figure 1). There was full consensus between the reviewers during the selection process of included papers.

**Study characteristics**

Combining results was not possible due to the heterogeneous study designs and patient characteristics across the included studies. Therefore only a general trend is noted.

Both subject demographics and health status for all studies are shown in Table 1. The number of symptomatic participants and the matching number of controls was generally small and ranged between seven [18] and fifty [19]. All but two of the included studies (8/10, 15, 17) had small sample size...
80%) enrolled mixed gender groups of healthy and symptomatic participants. The studies employed different age ranges of participants, with 20-40 years being most commonly enrolled (7/10, 70%).

General shortfalls in the documentation of technical aspects of COP acquirement were apparent. In addition, few authors described the baseline demographics of the participants in appropriate detail, including weight, height, age and gender (3/10, 30%).

There was a marked variation present in the included studies in terms of sampling duration, number of trials or the selection of the COP parameters. The studies often employed a combination of different positional and visual setups in order to investigate postural sway in various challenging positions. The resulting variation in results can be observed irrespective of the COP parameter chosen.

Table 2 shows the study characteristics for sway assessment in people with NSNP. The majority of trials were performed under both eyes open (EO) and eyes closed (EC) condition (4/6, 67%) with only a single repetition (5/6, 83%). Sway area and root mean square (RMS) amplitude were the most commonly used COP parameters.

<table>
<thead>
<tr>
<th>Study</th>
<th>Participant status</th>
<th>Gender (n)</th>
<th>Female</th>
<th>Male</th>
<th>Age in years Mean (SD)</th>
<th>Weight in kg Mean (SD)</th>
<th>Height in cm Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McPartland et al. [18]</td>
<td>NSNP *</td>
<td>6</td>
<td>1</td>
<td></td>
<td>39.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy *</td>
<td>4</td>
<td>3</td>
<td></td>
<td>39.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Michaelson et al. [21]</td>
<td>chronic NSNP</td>
<td>9</td>
<td>0</td>
<td></td>
<td>40 (9)</td>
<td>73 (18)</td>
<td>165 (7)</td>
</tr>
<tr>
<td></td>
<td>chronic WAD</td>
<td>6</td>
<td>3</td>
<td></td>
<td>44 (10)</td>
<td>79 (14)</td>
<td>171 (10)</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>13</td>
<td>3</td>
<td></td>
<td>41 (9)</td>
<td>70 (14)</td>
<td>168 (8)</td>
</tr>
<tr>
<td>Madeleine et al. [23]</td>
<td>chronic WAD *</td>
<td>7</td>
<td>4</td>
<td></td>
<td>33.3 (6.7)</td>
<td>73.4 (11.4)</td>
<td>173.3 (7.2)</td>
</tr>
<tr>
<td></td>
<td>healthy/induced NP</td>
<td>7</td>
<td>4</td>
<td></td>
<td>33.1 (6.8)</td>
<td>68.0 (12.5)</td>
<td>171.5 (6.3)</td>
</tr>
<tr>
<td>Treleaven et al. [19]</td>
<td>WAD (dizziness)</td>
<td>38</td>
<td>12</td>
<td></td>
<td>35.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>WAD (no dizziness)</td>
<td>38</td>
<td>12</td>
<td></td>
<td>35.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>28</td>
<td>22</td>
<td></td>
<td>29.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storaci et al. [26]</td>
<td>WAD</td>
<td>24</td>
<td>16</td>
<td></td>
<td>28.4 (8.8)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>23</td>
<td>17</td>
<td></td>
<td>33.9 (12.7)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Endo et al. [25]</td>
<td>WAD</td>
<td>19</td>
<td>13</td>
<td></td>
<td>39.0 (10.1)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>4</td>
<td>16</td>
<td></td>
<td>37.9 (9.3)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Treleaven et al. [27]</td>
<td>WAD</td>
<td>15</td>
<td>5</td>
<td></td>
<td>46.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>14</td>
<td>6</td>
<td></td>
<td>49.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Field et al. [22]</td>
<td>WAD</td>
<td>24</td>
<td>6</td>
<td></td>
<td>30.3 (1.3)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>NSNP</td>
<td>23</td>
<td>7</td>
<td></td>
<td>27.9 (1.3)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>23</td>
<td>7</td>
<td></td>
<td>26.8 (1.3)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Poole et al. [24]</td>
<td>NSNP</td>
<td>20</td>
<td>0</td>
<td></td>
<td>65-82</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>healthy</td>
<td>20</td>
<td>0</td>
<td></td>
<td>65-82</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vuillerme et al. [20]</td>
<td>healthy/induced NP</td>
<td>0</td>
<td>16</td>
<td></td>
<td>22.2 (1.8)</td>
<td>73.0 (11.8)</td>
<td>181.4 (6.4)</td>
</tr>
</tbody>
</table>


* one patient and one control participants did not participate in COP measurement.
- : not described.

80%) enrolled mixed gender groups of healthy and symptomatic participants. The studies employed different age ranges of participants, with 20–40 years being most commonly enrolled (7/10, 70%).

General shortfalls in the documentation of technical aspects of COP acquirement were apparent. In addition, few authors described the baseline demographics of the participants in appropriate detail, including weight, height, age and gender (3/10, 30%).

There was a marked variation present in the included studies in terms of sampling duration, number of trials or the selection of the COP parameters. The studies often employed a combination of different positional and visual setups in order to investigate postural sway in various challenging positions. The resulting variation in results can be observed irrespective of the COP parameter chosen.

Table 2 shows the study characteristics for sway assessment in people with NSNP. The majority of trials were performed under both eyes open (EO) and eyes closed (EC) condition (4/6, 67%) with only a single repetition (5/6, 83%). Sway area and root mean square (RMS) amplitude were the most commonly used COP parameters.

The study characteristics for trials enrolling WAD patients are presented in Table 3. Only a single recording was used in most cases (6/7, 86%), but in contrast to the NSNP studies, all study designs employed both visual conditions.

### Reliability of COP data

Table 4 gives an overview of how the studies included meet the ideal experimental setup for reliable data.

With the exception of one paper that only measured postural sway under visual deprivation [20], all of the studies included assessed COP with both eyes open and eyes closed. No study applied best practice experimental setup throughout.

### Pain assessment

All symptomatic participants experienced pain at the time of recording. About 75% of studies described the total neck pain duration prior to the COP measurements whereby the pain history ranged from acute, induced pain to 97 (SD 68) months. Of these studies, half (5/8, 63%) assessed both the duration and the perceived pain intensity by using either the visual analogue scale (VAS) [19-22] or the 11-box numeric rating scale (NRS-11) [23].

The perceived pain levels varied between the studies (Table 5). The pain intensity of WAD patients ranged between VAS 2.2 (SD 0.9) [22] and 4.9 (SD 2.3) [21],
### Table 2 Study characteristics and selected COP parameters measured in people with NSNP

<table>
<thead>
<tr>
<th>Study</th>
<th>Condition</th>
<th>Duration (sec)</th>
<th>Number of trials</th>
<th>Parameter</th>
<th>Neck pain Result (SD)</th>
<th>Healthy controls Result (SD)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>McPartland et al. [18]</td>
<td>normal stance</td>
<td>30</td>
<td>6</td>
<td>absolute</td>
<td>EO/F: 4.2</td>
<td>EO/F: 3.3</td>
<td>p &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>narrow stance</td>
<td>30</td>
<td>6</td>
<td>sway Vel †</td>
<td>EO/F: 4.3</td>
<td>EO/F: 3.4</td>
<td>ns</td>
</tr>
<tr>
<td>Michaelson et al. [21]</td>
<td>narrow stance,</td>
<td>20</td>
<td>1</td>
<td>sway Vel †</td>
<td>EC/F: 5.3</td>
<td>EC/F: 4.4</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>EO/F</td>
<td></td>
<td></td>
<td>sway area (mm²)</td>
<td>EO: 105 (73)</td>
<td>EO: 66 (47)</td>
<td>-</td>
</tr>
<tr>
<td>Madeleine et al. [23]</td>
<td>narrow stance,</td>
<td>45</td>
<td>1</td>
<td>displacement ampl. AP (mm)</td>
<td>EO: ~2.7 *</td>
<td>EO: ~2.1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>EO/F</td>
<td></td>
<td></td>
<td>displacement ampl. ML (mm)</td>
<td>EO: ~1.7 *</td>
<td>EO: ~1.0</td>
<td>-</td>
</tr>
<tr>
<td>Field et al. [22]</td>
<td>normal stance</td>
<td>30</td>
<td>1</td>
<td>AP RMS amplitude (mm)</td>
<td>EO/F: ~1.3</td>
<td>EO/F: ~1.2</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ML RMS amplitude (mm)</td>
<td>EO/C: ~1.4</td>
<td>EO/C: ~1.1</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>narrow stance, EO/EC/F/C</td>
<td>30</td>
<td>1</td>
<td>AP RMS amplitude (mm)</td>
<td>EO/F: ~3.3</td>
<td>EO/F: ~3.1</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ML RMS amplitude (mm)</td>
<td>EO/C: ~5.0</td>
<td>EO/C: ~4.0</td>
<td>ns</td>
</tr>
<tr>
<td>Poole et al. [24]</td>
<td>normal stance, EC/O/F/C</td>
<td>30</td>
<td>1</td>
<td>AP RMS amplitude (mm)</td>
<td>EO/F: ~2.3</td>
<td>EO/F: ~3.1</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ML RMS amplitude (mm)</td>
<td>EO/F: ~1.7</td>
<td>EO/F: ~1.8</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>narrow stance, EC/O/F/C</td>
<td>30</td>
<td>1</td>
<td>AP RMS amplitude (mm)</td>
<td>EO/F: ~4.2</td>
<td>EO/F: ~3.6</td>
<td>ns</td>
</tr>
<tr>
<td>Vuillerme et al. [20]</td>
<td>normal stance, EC/F</td>
<td>10</td>
<td>1</td>
<td>Variance (mm²)</td>
<td>~195 *</td>
<td>~13.5</td>
<td>p &lt; 0.05</td>
</tr>
</tbody>
</table>
### Table 2 Study characteristics and selected COP parameters measured in people with NSNP (Continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range (mm)</th>
<th>mVel (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>~ 20.3*</td>
<td>~15.5</td>
</tr>
<tr>
<td></td>
<td>~17.0*</td>
<td>~11.3</td>
</tr>
</tbody>
</table>

* The results presented have been extracted from bar-charts.
* Induced neck pain cases and healthy participants are identical.
- : not described
†: unit not described

AP: antero-posterior, BP: bipedal, displ. ampl: displacement amplitude, C: compliant (foam) surface, COP: center of pressure, EC: eyes closed, EO: eyes open, F: firm surface, ML: medial-lateral, mPos: mean position, mVel: mean velocity, ns: not significant (p > 0.05), NSNP: non-specific neck pain, RMS: root mean square, vel: velocity

### Table 3 Study characteristics and selected COP parameters measured in people with WAD

<table>
<thead>
<tr>
<th>Study</th>
<th>Condition</th>
<th>Duration (sec)</th>
<th>Number of trials</th>
<th>Parameter</th>
<th>WAD Result (SD)</th>
<th>Healthy controls Result (SD)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michaelson et al. [21]</td>
<td>narrow stance, EO/EC/F</td>
<td>20</td>
<td>1</td>
<td>sway area (mm²)</td>
<td>EO: 96 (57)</td>
<td>EO: 66 (47)</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: 269 (147)</td>
<td>EC: 109 (65)</td>
<td>p &lt; 0.01</td>
</tr>
<tr>
<td>Madeleine et al. [23]</td>
<td>narrow stance, EO/EC/F</td>
<td>45</td>
<td>1</td>
<td>displacement ampl. AP</td>
<td>EO: ~4.6</td>
<td>EC: ~2.1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(mm)</td>
<td>EC: ~6.0</td>
<td>EC: ~2.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>displacement ampl. ML</td>
<td>EO: ~2.2</td>
<td>EC: ~1.0</td>
<td>-</td>
</tr>
<tr>
<td>Treleaven et al. [19]</td>
<td>normal stance, EO/EC/F/C</td>
<td>30</td>
<td>1</td>
<td>total energy</td>
<td>EC: ~3.2</td>
<td>EC: ~1.2</td>
<td>-</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td>EO/F: ~0.80</td>
<td>EO/F: ~0.66</td>
<td>ns</td>
</tr>
<tr>
<td>Storaci et al. [26]</td>
<td>unclear stance, EO/EC/F</td>
<td>-</td>
<td>2</td>
<td>sway area (mm²)</td>
<td>EO: 136.6 (76.3)</td>
<td>EC: 84.1 (44.8)</td>
<td>-</td>
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<td></td>
<td></td>
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<td></td>
<td>EC: 246.3 (127)</td>
<td>EC: 180.1 (102)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>path length (mm)</td>
<td>EO: 407.5 (103)</td>
<td>EC: 338 (85.6)</td>
<td>-</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: 565.8 (151)</td>
<td>EC: 494.5 (145)</td>
<td>-</td>
</tr>
<tr>
<td>Endo et al. [25]</td>
<td>unclear stance, EO/EC/F</td>
<td>60</td>
<td>1</td>
<td>sway area (mm²)</td>
<td>EO: 102.8 (109)</td>
<td>EC: 35.0 (14.7)</td>
<td>p &lt; 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: 218.6 (207)</td>
<td>EC: 41.9 (25.2)</td>
<td>p &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mVel (mm/s)</td>
<td>EO: 18.6 (12.5)</td>
<td>EC: 13.8 (4.3)</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC: 32.8 (22.2)</td>
<td>EC: 17.9 (6.0)</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Treleaven et al. [27]</td>
<td>Normal stance, EO/EC/F/C</td>
<td>-</td>
<td>1</td>
<td>total energy AP</td>
<td>EO/F: ~1.2</td>
<td>EO/F: ~0.7</td>
<td>p &lt; 0.01</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>EO/C: ~1.6</td>
<td>EO/C: ~1.2</td>
<td>p &lt; 0.01</td>
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<td></td>
<td>EC/F: ~1.4</td>
<td>EO/F: ~0.9</td>
<td>p &lt; 0.01</td>
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<td>EC/C: ~1.6</td>
<td>p &lt; 0.01</td>
</tr>
<tr>
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<td>EO/F: ~0.6</td>
<td>EO/C: ~0.2</td>
<td>p &lt; 0.01</td>
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<tr>
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<td>p &lt; 0.01</td>
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<tr>
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<td>EC/C: ~0.9</td>
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</tr>
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<td></td>
<td></td>
<td></td>
<td>EO/F: ~1.2</td>
<td>EO/F: ~1.1</td>
<td>ns</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/C: ~1.6</td>
<td>EO/C: ~1.3</td>
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</tr>
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<td></td>
<td>EC/F: ~1.6</td>
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<td>EC/C: ~1.6</td>
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<td></td>
<td></td>
<td>EO/F: ~1.5</td>
<td>EO/F: ~1.3</td>
<td>ns</td>
</tr>
</tbody>
</table>
indicating mild to moderate pain. Individuals with NSNP perceived pain within a similar range and rated their intensity from VAS 3.2 (SD 0.4) \[22\] to 5.2 (SD 1.6) \[21\].

Neck pain and postural sway

Generally there was a great variability in the reported COP measures. The results of the included studies indicated that patients with any form of neck pain exhibited a greater postural instability than healthy controls, a difference that was more pronounced in WAD patients.

In people with NSNP, a significant difference compared to healthy individuals was only observed in a minority of recordings (9/38, 24\%) across all positional and visual conditions. Statistical significance was reached only in normal stance under visual deprivation on a firm surface \[20,22,24\] as well as with open eyes on both firm \[18\] and compliant surface \[24\]. In narrow stance the differences reached \( p \leq 0.05 \) with eyes open \[24\] and closed \[22\] on a firm surface as well as on a foam pad with eyes open \[24\]. One study failed to report levels of significance \[21\].

Table 3 Study characteristics and selected COP parameters measured in people with WAD (Continued)

<table>
<thead>
<tr>
<th>Study</th>
<th>Sampling frequency</th>
<th>Cut-off frequency</th>
<th>Duration</th>
<th>Number of repetitions</th>
<th>Visual condition</th>
<th>Surface</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Field et al. [22]</td>
<td>30</td>
<td>1</td>
<td>AP RMS amplitude (mm)</td>
<td>EO/C: ~1.7</td>
<td>EO/C: ~1.6</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>EO/F: ~1.7</td>
<td>EC/F: ~1.5</td>
<td>p &lt; 0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~1.9</td>
<td>EC/C: ~1.9</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ML RMS amplitude (mm)</td>
<td>EO/F: ~1.4</td>
<td>EO/F: ~1.2</td>
<td>p &lt; 0.05</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/F: ~1.5</td>
<td>EC/F: ~1.1</td>
<td>p &lt; 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~3.1</td>
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<td></td>
<td></td>
<td></td>
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<td>EC/C: ~2.4</td>
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<td>Narrow stance, EO/EC/F/C</td>
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<td>EO/F: ~2.4</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~5.0</td>
<td>EC/O: ~4.1</td>
<td>p &lt; 0.05</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EC/C: ~7.0</td>
<td>EC/C: ~5.6</td>
<td>p &lt; 0.05</td>
<td></td>
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<tr>
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<td></td>
<td>ML RMS amplitude (mm)</td>
<td>EO/F: ~4.2</td>
<td>EO/F: ~3.1</td>
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<td>EC/O: ~4.4</td>
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<td>EC/C: ~7.9</td>
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</tr>
</tbody>
</table>

*: not described.

∞ The results presented have been extracted from bar-charts.


Table 4 Reliability criteria

<table>
<thead>
<tr>
<th>Study</th>
<th>Sampling frequency</th>
<th>Cut-off frequency</th>
<th>Duration</th>
<th>Number of repetitions</th>
<th>Visual condition</th>
<th>Surface</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>McPartland et al. [18]</td>
<td>~100 Hz</td>
<td>10 Hz</td>
<td>≥ 90 sec</td>
<td>3-5</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Michaelson et al. [21]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Madeleine et al. [23]</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Treleaven et al. [19]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Storaci et al. [26]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Endo et al. [25]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Treleaven et al. [27]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Field et al. [22]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Poole et al. [24]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Vuillerme et al. [20]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

http://chiromt.com/content/19/1/13
In cases of acutely induced neck pain, a marked immediate increase in postural sway could be observed. While Vuillerme et al. [20] found a significantly increased mean sway velocity and area, no p-values were calculated for the study by Madeleine et al. [23] (Table 2).

People with WAD also showed an increased postural sway, indicated by a greater COP sway area [21,25,26], total energy [19,27], root mean square (RMS) amplitude and mean sway velocity [22,25]. In contrast to NSNP patients, the variance in COP excursion compared to healthy controls was significant in the majority of experimental setups, although two studies did not report levels of significance [23,26]. The increase in postural sway in antero-posterior (AP) direction was more significant than in the medio-lateral (ML) plane [22,23] (Table 3).

Disability assessment
Only three studies [19,22,24] assessed the level of disability in neck pain patients using the neck disability index (NDI) [28]. The NSNP patients scored NDI disability percentages between 21.5% (SD 1.4) [22] and 23.95% (SD 2.3) [24] while people with WAD had higher levels of impairment at 36.9% (SD 2.8) [22]. Scores from 21-40% indicate moderate disability.

Discussion
Summary of evidence
The heterogeneous study designs and experimental setups did not allow pooling of data or any direct comparison of results across the studies. In addition, the poor overall documentation of the experimental setups, particularly with regards to participant demographics and technical aspects such as sampling frequency and cut-off frequency, impaired full interpretation. However, despite the great variability there was enough consistency in results to show that patients suffering from NSNP and WAD exhibit an increased COP sway compared to healthy individuals, especially in AP direction. Unfortunately, the magnitude of these differences in postural sway cannot be summarily expressed in terms of specific percentages or values. As a result, only a general trend is noted.

As we outlined in a previous systematic review [17], the reliability of COP measurements is primarily determined by the six main factors (Table 4). Although only two of the included studies fulfilled more than half of the recommended reliability criteria [18,23], it is worth bearing in mind that studies considering less than all six criteria may still present fairly reliable results.

While a general trend towards decreased postural stability can be observed irrespective of the origin of the pain, the altered sway pattern appears to correlate with the associated degree of proprioceptive impairment. This is signified by the generally greater COP excursions in WAD cases [21-23] where damage to proprioceptive structures and neck musculature due to the sustained trauma may be expected. In addition, higher pain intensities or the underlying neurological or vestibular impairments observed in several studies [21,25] may be the determining factor in the reported highly significant differences in sway pattern compared to healthy controls. The lack of comparable
data does not allow the interpretation of previous pain duration or associated perceived disability in this context. While some WAD patients may have also been included in NSNP studies, it appears unlikely that this affected the overall results.

We have decided to include studies using induced pain in our review. While this cannot be considered similar to (chronic) NSNP, it may nevertheless mimic many alterations in sensorimotor functions documented in acute clinical pain conditions, although it should be noted that it does not replicate any potential long term neurological adaptation. Both experiments resulted in significantly altered sway pattern which may underline the role of acute “pain inhibition” [8] in the observed postural response. However, the COP sway area measured was nevertheless smaller than reported in people with WAD [23] which may underline the likely role of proprioceptive impairment associated with the pain in the development of COP excursions of larger magnitude.

Visual deprivation caused an increase in postural sway in numerous studies of healthy participants [29-32] and has shown to be a major challenge to the balance systems in studies investigating the effect of non-specific low back pain on postural stability [29,33,34]. Nevertheless, statistically significant differences were not found in a number of NSNP studies (Table 2). In addition to issues arising from the experimental setups and the generally small sample sizes of seven [18] to thirty [22] symptomatic participants, the variations in the perceived pain intensities may offer an explanation.

Pain severity has shown to be a determining factor in non-specific low back pain cases [16] where a significant, linear increase in postural sway was observed beginning at a NRS-11 score of 5. If this can be applied to NSNP patients as well, low pain intensities at the time of recording such as those reported by Field et al. [22] may well explain the fact that no significant differences could be identified, while patients suffering from more severe pain exhibited significantly increased postural sway compared to healthy controls [20].

If rather small differences in COP measures between the groups can be anticipated, the choice of appropriate sway parameters is important. However, only Vuillerme et al. [20] and Endo et al. [25] used mean velocity (mVel), a parameter that has shown both consistently high reliability [17] and discriminative value in pain conditions [15]. Despite a small sample size and low scores for the reliability of the experimental setup, they found highly significant differences with eyes open [25] and under both visual conditions [20].

The effect of ageing can be observed when comparing the studies by Field et al. [22] and Poole et al. [24]. Although the methodologies are very similar, varying results were reported. This may be explained by the fact that the latter enrolled elderly patients (65-82 years compared to 27-30 years). Older individuals exhibit increased COP excursions [35] and any pre-existing deficits in proprioception associated with ageing may add to the alterations caused by the neck pain.

Overall, the lack of data available, no conclusions can be drawn regarding a possible relationship between postural stability and perceived pain or disability levels. For the same reason, no conclusion about the effect of impairments in cervical ROM is possible.

Clinical considerations

At this point, there are several important limitations to the application of COP measures in the assessment of postural sway in a clinical setting:

Although the results tempt us to hypothesize a correlation between the magnitude of COP excursions and the extent of damage to proprioceptive structures, the causative factor for the altered postural sway pattern remains largely unclear in people with WAD and NSNP. The question still remains whether the increased COP excursions are predominantly related to the previously described physiological changes due to chronic pain perception, acute or chronic damage to proprioceptive structures in the neck or acute “pain inhibition” [8]. If the latter mechanism is mainly responsible or if the proprioceptive impairment is of acute and reversible nature, monitoring neck pain patients during their treatment and rehabilitation process may aid as an objective tool in assessing the patient’s progress. If long-term neuro-physiological changes are primarily involved, individually varying recovery time frames may render such measurements less useful.

Finally, the data available is insufficient to determine whether some form of correlation between the neck pain intensity, its duration or the perceived disability and the magnitude of postural sway exists. As a linear relationship between pain intensity and COP sway velocity has been demonstrated in patients with non-specific low back pain [16], further research is necessary to investigate whether this also applies to people with neck pain. If this can be established COP may have a clinical role as an instrument of measurement for neck pain patients.

Limitations

Although employing two reviewers to individually search the literature constitutes a major strength of this review, there are limitations. For example, the search strategy was limited to six key databases which might not have identified all relevant papers. To overcome this, a dynamic search strategy was employed with selected hand searches of reference lists. Due to the aim of this review, only COP measures derived from bipedal static tasks were included.
Conclusions

Patients with neck pain of both whiplash associated disorder and non-specific neck pain exhibit greater postural instability than healthy controls. This difference is more pronounced under visual obstruction and may be attributed to either acute pain inhibition or diminished proprioceptive input from the cervical spine and neck muscles due to long-term neurological adaptations although additional cognitive and behavioral factors cannot be ruled out. People with WAD show greater COP excursions than NSNP patients and this may be due to the potentially increased damage to cervical proprioceptive structures associated with the sustained neck trauma.

While the presence of pain itself appears associated with increased postural sway, there is insufficient data to suggest a relationship between pain intensity, previous pain duration or the level of perceived disability and the magnitude of COP excursions.

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Authors’ contributions
AR and Tino Bos (TB) carried out the literature search and both participated in the selection of the included papers. AR drafted the manuscript and performed the statistical analysis. RF and BW helped with the design of the study and drafting the manuscript. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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References


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Is there a relationship between pain intensity and postural sway in patients with non-specific low back pain?

Alexander Ruhe1*, René Fejer2† and Bruce Walker3†

Abstract

Background: Increased center of pressure excursions are well documented in patients suffering from non-specific low back pain, whereby the altered postural sway includes both higher mean sway velocities and larger sway area. No investigation has been conducted to evaluate a relationship between pain intensity and postural sway in adults (aged 50 or less) with non-specific low back pain.

Methods: Seventy-seven patients with non-specific low back pain and a matching number of healthy controls were enrolled. Center of pressure parameters were measured by three static bipedal standing tasks of 90 sec duration with eyes closed in narrow stance on a firm surface. The perceived pain intensity was assessed by a numeric rating scale (NRS-11), an equal number of patients (n = 11) was enrolled per pain score.

Results: Generally, our results confirmed increased postural instability in pain sufferers compared to healthy controls. In addition, regression analysis revealed a significant and linear increase in postural sway with higher pain ratings for all included COP parameters. Statistically significant changes in mean sway velocity in antero-posterior and medio-lateral direction and sway area were reached with an incremental change in NRS scores of two to three points.

Conclusions: COP mean velocity and sway area are closely related to self-reported pain scores. This relationship may be of clinical use as an objective monitoring tool for patients under treatment or rehabilitation.

Background

Increased postural sway is well documented in patients suffering from non-specific low back pain (NSLBP) [1] and a variety of theories exist regarding the effect of NSLBP on body sway. Postural control mechanisms are believed to be affected by damage to sensory tissues in the lumbar spine and trunk [2]. This deterioration of proprioceptive information reduces the accuracy of the sensory integration processes resulting in an imprecise estimation of the center of mass position [3], thereby inhibiting compensatory center of pressure (COP) shifts.

Acute “pain interference” [4] has also been proposed as a possible cause with discharge from high-threshold nociceptor afferents in the low back interfering with spinal motor-pathways [5] and the motor cortex [6]. In addition, pain may cause an increased pre-synaptic inhibition of muscle afferents [7] and affect the central modulation of proprioceptive spindles of muscles [8], thereby causing prolonged latencies by a decrease in muscle spindle feedback.

As outlined in our systematic literature review [1], several factors such as age [9-11], gender, weight [12], and height [13] have been shown to exhibit a significant effect on postural sway. The aim of this study is to investigate whether COP excursions are also affected by pain severity and pain duration and if so, to further describe this relationship. This relationship is worthy of investigation as it may show clinical significance for the application of COP measures.

To our knowledge, this is the first study to investigate this clinical question with a best practice experimental setup and also the first to comprehensively assess the relationship between pain and COP excursions over a...
wide spectrum of pain scores when compared to healthy controls.

**Methods**

**Subjects**

We aimed at enrolling around 80 participants for both symptomatic and control group. Previous sample size calculations for a group of controls and symptomatic patients with an NRS-11 score of 5.0 ± 2.1 using an Altman Nomogram [14] suggested recruitment of around 50 symptomatic and healthy participants each. We decided to exceed this number in order to compensate for potential dropouts.

All new patients entering a private chiropractic clinic in Wolfsburg, Germany were asked on the phone whether they would take part in this study. The healthy controls were friends and partners of already enrolled participants and were initially approached by them regarding the possibility of participation. If they displayed interest they were asked to contact the clinic for further details. After verbal and written information had been given, the subjects consented to participate in this study, which was approved by the Murdoch University Human Research Ethics Committee (Approval 2010/173).

The cut-off age for both controls and symptomatic individuals was 50 years, as after that age related impairments to postural stability could not be excluded [9-11].

Inclusion criteria for the symptomatic participants were NSLBP of any duration and the presence of pain ≥ 2 on the NRS-11 scale on the day of the postural sway recordings. Participants were excluded if the pain went below the gluteal fold, there were positive nerve root findings, serious spinal deformities, any condition that might affect balance (e.g. whiplash associated disorder or vestibular pathologies) or previous significant injuries such as traumatic damage to the spine or spinal surgery. No pain medication was allowed within 24 hours prior to the recordings. Participants were also excluded if they were unable to perform the postural sway recording either due to pain or other reasons. We aimed at enrolling around 10 patients for the 9 pain intensity groups (NRS 2-10).

For the purpose of this study, healthy was defined as the absence of any self-reported neurological or musculoskeletal impairments, pain or disability for a minimum of 6 months prior to the time of evaluation. Specifically, individuals with a history of low back pain within 6 months or previous injury to the neck or lower extremities, any known balance problems or the usage of medication associated with pain suppression or altered sensory perception were excluded. The physical examination of the control group must also have ruled out any back or extremity complaints or significant biomechanical impairments that might influence the measurements.

**Procedures**

Prior to the COP measurements, a physical examination was conducted on all participants by two experienced and trained chiropractors (TB and AS) who were otherwise not involved in the study. This procedure aimed to assess whether the volunteers met the criteria for their respective group and met the physical demands of the study. The NSLBP participants were further asked to describe their pain intensity at the time of recording by means of an NRS-11, a rating scale ranging from 0 (no pain) to 10 (worst possible pain) [15].

The experimental setup was based on an earlier literature review where a best practice setup for obtaining reliable COP data was published [16]. Accordingly, trials were conducted with eyes closed as the data obtained shows higher reliability than with eyes open. We further considered that the loss of visual input would prove an additional challenge to the balance system. In this way deficits in proprioception may be more easily detected and the discriminative value of the measurement between healthy controls and symptomatic NSLBP participants enhanced.

The system used for this study was a Metitur Good Balance GB300® CE (Metitur Oy, Finland). Signals were sampled at 100 Hz, amplified and converted from analogue to digital. High frequency noise was reduced by a low-pass filter with a cut-off frequency of 10 Hz.

Mean velocity (mVel) was chosen as the main COP parameter as this has consistently shown to be both reliable [16] and discriminative for NSLBP [1]. It is described by taking the total distance of the COP path travelled in the respective direction and dividing it by the sampling duration. In addition, the 90% circle diameter was included to offer a broader spectrum of analysis. This parameter refers to the diameter of a circle containing 90% of the COP path travelled over a given time.

The participants were asked to remove their shoes and stand upright on the forceplate with their eyes closed, the head erect and their arms hanging loosely by their sides. The foot position was narrow stance with toes and heels touching. For the duration of the recording, the participants were further instructed to “stand as still as possible” [17].

Three successive trials of 90 seconds duration each were conducted with a preceding 5 sec adaption period that was not recorded. Rest periods of 60 sec were provided between each trial during which the participants were allowed to sit down while maintaining their original foot position on the forceplate. All participants were
asked afterwards whether pain or discomfort may have influenced their balance performance.

All tests were conducted in a quiet room with normal temperature. The forceplate was calibrated prior to the recordings and further underwent an automatic calibration check before each trial.

**Data analysis**

**Age effects**

To test if postural sway is influenced by age [9-11], the healthy participants were subdivided into two age ranges (20-35 and 36-50 years) and subsequently compared to see if they statistically differ from each other. If, however, our study showed no significant differences, the age groups were to be combined for further analysis to reduce the risk of type-II error.

**Reliability**

To test the reliability of the COP measures for this experimental setup for both controls and pain sufferers, the two-way random-effect intra-class correlation coefficient (ICC2,k) as described by Shrout and Fleiss [18] was computed using absolute agreement. For the purpose of this study it was interpreted using the following criteria: 0.0-0.39 poor, 0.40-0.59 fair, 0.60-0.74 good and 0.75-1.00 excellent [19]. In addition, the 95% confidence intervals (CI) and the standard error of measurement (SEM) [20] were calculated.

**Relationship between pain intensity and postural sway**

We also tested the assumptions of homogeneity of variance (Levene statistic) and normality, where Shapiro-Wilk test was conducted for all independent variables and the dependent variables separately per pain group. The COP data was further analyzed using the Games-Howell test. Means, standard deviations (SDs) and 95% confidence intervals (CIs) were calculated for all dependent variables.

Stepwise univariate regression analysis was conducted to assess for the possible effect of each of the following variables: age, gender, weight, height, pain intensity and previous pain duration on COP mVel and 90% circle diameter. This was followed by a multivariate regression analysis where independent variables that showed a significant effect during univariate analysis were included.

To investigate the appropriate form of regression analysis, the SPSS Curve Estimation function was applied to scatter plots for variables stated above (independent variables) and the COP parameters (dependent variables). In addition, collinearity diagnostics were applied. The level of statistical significance was set at $p \leq 0.05$.

All data were exported to PASW® Statistics 18 (SPSS Inc, 2009) for statistical analysis.

**Results**

**Subjects**

Eighty-two individuals suffering from NSLBP initially volunteered to participate in this study. We did not reach our target number of at least 10 NSLBP participants for NRS scores 9 (n = 2) and 10 (n = 0) and therefore only included NRS scores 2-8 with 11 NSLBP participants each. Five symptomatic participants were excluded as they exhibited severe pain (n = 4) or an antalgic posture (n = 1) when standing and were unable to complete the tests. This left a total of 77 NSLBP sufferers (37 females, 45%) to which a matching number of healthy controls were enrolled. All participants were able to complete the trials without difficulty and did not report increased pain or discomfort during the COP recordings. The characteristics of the participants are shown in Table 1.

**Age groups**

Both age groups had a similar number of healthy participants with n = 36 for 18-35 yrs and n = 41 for 36-50 yrs. As there was no statistically significant difference in COP measures between the two groups (Table 2), the data were combined and analyzed for the control group as a whole.

**Reliability**

With three recordings being averaged from the both healthy controls and symptomatic participants, the included COP parameters reached good reliability throughout (Table 3).

---

### Table 1 Demographic and functional characteristics

<table>
<thead>
<tr>
<th></th>
<th>NSLBP Age 20-35 (n = 32)</th>
<th>Healthy controls Age 20-35 (n = 36)</th>
<th>Statistical difference p-value</th>
<th>NSLBP Age 36-50 (n = 45)</th>
<th>Healthy controls Age 36-50 (n = 41)</th>
<th>Statistical difference p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>28.9 ± 4.7</td>
<td>29.8 ± 4.4</td>
<td>0.89</td>
<td>44.1 ± 4.3</td>
<td>43.5 ± 5.5</td>
<td>0.67</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.0 ± 6.6</td>
<td>177.2 ± 7.4</td>
<td>0.36</td>
<td>179.2 ± 7.6</td>
<td>176.9 ± 6.9</td>
<td>0.37</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>77.6 ± 9.5</td>
<td>77.3 ± 11.7</td>
<td>0.047</td>
<td>80.8 ± 12.8</td>
<td>76.9 ± 8.8</td>
<td>0.71</td>
</tr>
<tr>
<td>BMI</td>
<td>24.3 ± 2.7</td>
<td>24.9 ± 3.9</td>
<td>0.60</td>
<td>25.1 ± 2.9</td>
<td>24.5 ± 1.9</td>
<td>0.11</td>
</tr>
<tr>
<td>NRS-11 (0-10)</td>
<td>49 ± 1.9</td>
<td>N/A</td>
<td>N/A</td>
<td>5.1 ± 2.1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Previous pain duration (weeks)</td>
<td>199 ± 33.6</td>
<td>N/A</td>
<td>N/A</td>
<td>187 ± 30.5</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Values are mean ± SD
Relationship between pain intensity and postural sway
As a general trend, a steady linear increase in mVel AP/ML and 95% circle diameter direction can be observed. Levene’s Tests showed no homogeneity of variance ($p \leq 0.018$) while Shapiro-Wilk test indicated a normal distribution of the independent and dependent variables ($p \geq 0.11$).

Compared to healthy controls, a significant difference ($p \leq 0.01$) in mVel was present in NSLBP participants beginning at an NRS score of 3 in ML direction. In AP direction, statistical significance ($p \leq 0.05$) was also reached at a pain intensity of 3 with an increase in significance from 5 to 8 ($p \leq 0.001$) (Figure 1).

Compared to healthy controls, a significant difference in 90% circle diameter was only present at NRS scores of 6, 7 and 8 ($p \leq 0.001$) (Figure 2).

The differences in postural sway between pain scores as assessed by Games-Howell are presented in Tables 4 and 5. With regards to mVel differences between the individual pain scores, significance was reached at lower NRS scores in ML compared to AP direction (Table 4).

Finally, the relative differences between pain scores for the parameter 90% circle diameter are demonstrated in Table 5. The same trend as seen with mean sway velocity can be observed. However, at pain intensities 2 and 3, significant differences between pain scores are present at larger intervals (3 NRS scores compared to 1-2 at mVel ML/AP).

Regression analysis
The SPSS Curve Estimation function showed that a linear relationship was the most suitable line of fit ($p \leq 0.001$). Hence, linear regression was used for further analyses of the data. No co-linearity between the variables was determined.

Table 2 Comparison of COP data between the age groups

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>Healthy controls 20-35 yrs (n = 36)</th>
<th>Healthy controls 36-50 yrs (n = 41)</th>
<th>Statistical difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>mVel ML (mm/s)</td>
<td>11.8 ± 2.5</td>
<td>12.0 ± 2.7</td>
<td>0.28</td>
</tr>
<tr>
<td>mVel AP (mm/s)</td>
<td>9.1 ± 2.7</td>
<td>9.5 ± 2.1</td>
<td>0.27</td>
</tr>
<tr>
<td>90% circle diameter (mm)</td>
<td>11.6 ± 2.8</td>
<td>12.0 ± 2.4</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Values are mean ± SD
AP: antero-posterior, mVel: mean velocity, ML: medio-lateral

Table 3 Reliability of COP measures

<table>
<thead>
<tr>
<th>COP parameter</th>
<th>NSLBP (n = 77)</th>
<th>Healthy controls (n = 77)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC2,k 95%CI SEM</td>
<td>ICC2,k 95%CI SEM</td>
<td></td>
</tr>
<tr>
<td>mVel ML</td>
<td>0.85 0.79-0.99 0.96</td>
<td>0.89 0.73-0.97 0.89</td>
<td></td>
</tr>
<tr>
<td>mVel AP</td>
<td>0.83 0.76-0.88 0.86</td>
<td>0.85 0.63-0.96 0.96</td>
<td></td>
</tr>
<tr>
<td>90% circle diameter</td>
<td>0.71 0.61-0.79 1.29</td>
<td>0.69 0.57-0.77 1.44</td>
<td></td>
</tr>
</tbody>
</table>

AP: antero-posterior, mVel: mean velocity, ML: medio-lateral

The univariate regression analysis included the variables gender, age, weight, height, previous pain duration and pain intensity. With the exception of previous pain duration, all other independent variables exhibited a significant effect on mVel AP/ML and 90% circle diameter and were consequently included in the multivariate analysis. This further analysis showed that only pain intensity exhibited a significant effect on the selected COP parameters.

For mean velocity and pain intensity, the regression analysis was a reasonably good fit, describing 53.0% of the variance in mVel ML and 40.0% in mVel AP ($R^2_{adj} = 51.0\%$ and $R^2_{adj} = 38.4\%$ respectively), the overall relationship was highly significant in both ML and AP direction ($F = 40.8, p < 0.001$ and $F = 24.9, p < 0.001$ respectively). Mean sway velocity increased by 1.53 mm/s for every extra pain level in ML, and by 1.27 mm/s for every extra pain level in AP direction.

The regression analysis for the parameter 90% circle diameter and pain intensity was a poor fit, describing just 18.7% of the variance in circle diameter ($R^2_{adj} = 16.5\%$). The overall relationship, however, was highly significant ($F = 8.6, p < 0.001$). The 90% circle diameter of the COP excursion increased by 0.6 mm for every extra pain level.

Discussion
We were unable to enroll a sufficient number of NSLBP participants for all pain intensity groups to allow analysis of all 10 NRS scores. This may be explained by the fact that patients with NRS scores of 9 and higher are not commonly encountered in a chiropractic practice as the potential severity of the condition warrants medical attention instead.

We were able to demonstrate a linear relationship between pain intensity and postural sway velocities in both AP and ML direction as well as for the parameter 90% circle diameter. This is in agreement with a general observation by Lihavainen et al. [21] who conducted a similar study in a geriatric population. They did not, however, investigate postural sway related to the individual pain scores but reached their conclusions based on a subdivision into mild or moderate/severe pain only.

Even though an increased sway velocity started at a lower pain score in the AP direction, the overall...
difference compared to healthy controls was similar to that in the ML direction. On the other hand, the ML sway velocity increased at a faster rate. In addition, this study confirms the altered postural sway characteristics previously reported in a systematic review of NSLBP sufferers [1]. The review noted higher COP mVel values (particularly the AP direction) and a larger sway area compared to healthy controls was described.

The non-overlapping 95% CIs associated with NRS scores at higher pain intensities, particularly with mVel AP/ML, are surprising and may be attributable to our standardized experimental setup and selection of participants. Such a clear subdivision appears unlikely at first sight due to the inherently varying pain perception between individuals.

As the 90% circle diameter is exclusively used with the Metitur system, it is not possible to put the respective results into context. However, it corresponds to the various parameters applied in the literature to describe COP sway area and may therefore offer at least limited comparability.

Our data, however, does not allow for an explanation of the underlying mechanism of the observed pain associated alterations in COP sway velocity. However, as previous pain duration did not exhibit a significant effect on postural sway as pain intensity has, this may suggest that pain interference [4] may be the determining factor. Neuro-physiological changes, on the other hand, are rather dependent on pain duration and therefore a significant time effect would have been expected. Future studies assessing postural sway before and after acute pain stimulation or using analgesics in chronic and acute NSLBP participants may add valuable information in this respect.

Furthermore, as no other studies have looked into the relationship between a broader range of pain intensities and COP measures it is not possible to compare our results.

At lower and medium pain intensities there was no apparent change in the COP parameters. This may be due to participants finding it difficult to decide on their “true” score, NRS-5 for example shows the widest standard deviations across all parameters. This may therefore explain why no statistically significant differences were observed between lower pain scores (NRS 2-4) for most parameters and may account at least partially for the variability in the associated COP measurements. However, as the confidence intervals across all pain

Figure 1 Relationship between pain intensity and mean sway velocity in AP and ML. The horizontal line and the grey area indicate the mean score of healthy controls and the standard deviations respectively. The vertical lines indicate standard deviations; the boxes show mean and 95% CIs respectively. Levels of significance compared to controls: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.\n
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scores remain fairly consistent, the variability of the postural sway measurements most likely reflects individual variations within the COP excursions. The results also suggest that the neurological alteration previously described [4-8] may only have an impact on COP measures at medium to high intensities (i.e. NRS ≥ 5).

In contrast to other studies [9-13], we could not demonstrate any significant effect of age, height, weight or gender on COP excursions in the patient group. This may be attributed to the demographics and physical characteristics of the participants as well as our COP measurement protocol. Our results were derived using a protocol based on best evidence [16], nevertheless future studies are needed to confirm these findings using the same protocol.

Table 4 Sway differences between NSLBP participants and pain free controls using NRS-11 scores for mVel AP and ML

<table>
<thead>
<tr>
<th>NRS-11 Score</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
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Table 5 Sway differences between NSLBP participants and pain free controls using NRS-11 scores for 90% circle diameter

<table>
<thead>
<tr>
<th>NRS-11 Score</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
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<tr>
<th>NRS-11 Score</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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</table>

Levels of significance: * p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001

n.s.: not significant (p > 0.05)
Clinical considerations

The COP measurement protocol used in this study may in future be suitable as an objective outcome measure for clinical monitoring purposes. However, the results are unidirectional in that increasing pain was associated with increasing postural sway. We have not established that decreasing pain leads to a decreasing postural sway.

Secondly, given the linear relationship between pain intensity and, for example, mVel, a clinically significant decrease of two points on a pain NRS [20] is equivalent to a reduction in mean sway velocity of 3.6 mm/s in ML and of 3.0 mm/s in AP direction. These changes lie between 1 and 2 standard deviations from the mean. It remains to be seen if such a reduction is also clinically significant.

In addition, this study indicates that any future sample size calculations for COP measurements involving pain sufferers should be considered in the light of the respective perceived intensity. Depending on the research purpose, the inclusion criteria may focus on those with NRS-scores of 5 or higher to reach significance compared to controls more readily.

The results may also cast a new light on the interpretation of studies that reported no significant differences in postural sway between symptomatic individuals and healthy controls. In those instances (e.g. Brumange et al. [22] and Mok et al. [23]), these observations may be attributable to the low perceived pain intensities of the NSLBP participants enrolled.

There is evidence that higher COP sway is associated with a higher risk of falling in the elderly [24] and sustaining injuries as a consequence, although this is subject to debate [25,26]. Our results did not include geriatric participants and therefore cannot be generalized to that population, however our data may nevertheless underline the importance of suitable pain control in elderly pain sufferers to avoid falls.

In addition, as pain interference appears a likely underlying mechanism, the focus of a rehabilitative approach in pain sufferers with increased COP excursions should be on pain reduction rather than proprioceptive training.

Future studies may also show a role for COP measurements as part of a suite of other procedures to identify malingers. Even if the individual is aware that pain is associated with greater COP excursions, a study with pseudo-malingers showed that imitating pain related sway pattern is difficult at best and the average results for sway velocity and sway area greatly exceeded those expected from a real pain sufferer [27].

Strengths and Limitations

The major strength of this study is in its best practice experimental setup which ensured reliable data collection. Our inclusion and exclusion criteria further prohibited our overall results from being affected by demographic or anthropometric factors.

In this cross-sectional study the subjective nature of pain perception and therefore pain rating may have influenced the results. In addition, pain perception between younger and older NSLBP participants varies and a decrease in pain perception in geriatric individuals has been described [28]. Although this does not affect our sample groups with a cut-off age of 50 yrs, it nevertheless prohibits our results to be generalized to elderly patients.

While significant differences in postural sway compared to healthy controls could be demonstrated in our patient population, the overall number of participants per NRS score was still comparatively small. Our results are therefore prone to be affected by extreme COP measures. Other sample groups with identical NRS scores may therefore show varying results. However, we expect the linear trend to be preserved. Similar studies with an identical experimental setup and larger sample sizes should be conducted to confirm our results.

Conclusions

Despite the subjective nature of pain perception and the unclear causative factors, the results of this study show that in adults (18 and 50 years) with NSLBP, increasing COP sway velocity increases linearly with increasing perceived pain intensity greater than 4 on an NRS scale. This trend, while less obvious, is also apparent for the parameter 90% circle diameter.

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We would like to thank Tino Bos for his valuable contribution by conducting the physical examinations and the clinic staff for their continuous support in recruiting the participants and organizing measurement appointments.

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Authors’ contributions

AR carried out the COP measurements, conducted the statistical analysis and drafted the manuscript. RF and BW participated in the study design and assisted in drafting the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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1. Ruhe A, Fejer R, Walker B: Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: a systematic review of the literature. European Spine Journal, official publication of the European Spine Society, the


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