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Title

The effect of technique change on knee loads during sidestep cutting

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Running Title

Technique and knee loads in sidestep cutting

Abstract

Purpose: To identify the effect of modifying sidestep cutting technique on knee loads and predict what impact such change would have on the risk of non-contact anterior cruciate ligament injury. **Methods:** A force platform and motion analysis system were used to record ground reaction forces and track the trajectories of markers on 15 healthy males performing sidestep cutting tasks using their normal technique and nine different imposed techniques. A kinematic and inverse dynamic model was used to calculate the three dimensional knee postures and moments. **Results**: The imposed techniques of foot wide, torso leaning in the opposite direction to the cut resulted in increased peak valgus moments experienced in weight acceptance. Higher peak internal rotation moments were found for the foot wide and torso rotation in the opposite direction to the cut techniques. The foot rotated in technique resulted in lower mean flexion/extension moments while the foot wide condition resulted in higher mean flexion/extension moments. The flexed knee, torso rotated in the opposite direction to the cut and torso leaning in the same direction as the cut techniques had significantly more knee flexion at heel strike. **Conclusion:** Sidestep cutting technique had a significant effect on loads experienced at the knee. The techniques which produced higher valgus and internal rotation moments at the knee, such as foot wide, torso leaning in the opposite direction to the cut and torso rotating in the opposite direction to the cut, may place an athlete at higher risk of injury as these knee loads have been shown to increase the strain on the anterior cruciate ligament. Training athletes to avoid such body positions may result in a reduced risk of non-contact anterior cruciate ligament injures.

Key Words

Anterior Cruciate Ligament; Injury; Injury Prevention; Biomechanics

Introduction

Paragraph Number 1. Injuries to the anterior cruciate ligament (ACL) are serious, costly and unfortunately common in many different sports including; basketball, soccer, lacrosse, European handball and Australian football (9, 31, 33). In order to return to sport from a ruptured ACL an injured athlete usually requires surgery, followed by nine to twelve months of rehabilitation (32). The approximate cost of an ACL reconstruction is US$17,000, with the total cost of all ACL reconstructions in a given year in the United States estimated at US$850,000,000 (14). Individuals who have suffered an ACL injury also have significantly increased risk of developing knee joint osteoarthritis by the age of 50 years (12).

Paragraph Number 2. Anterior cruciate ligament injuries can be classified into two broad groups; contact and non-contact. Across various sports non-contact injuries have been found to make up 50 to 80% of ACL injuries (1, 6, 9). As a large percentage of injuries are non-contact this indicates there is potential to reduce the number of ACL injuries occurring in sports. This may be achieved by changing how the person performs the injury prone maneuvers with appropriate training. Lloyd (22) stated that training programs to prevent ACL injuries should include balance, plyometric and technique components. Although there have been several studies examining the effect of balance and plyometric training on the risk of ACL injury (7, 16, 18, 33), only a few recent studies have investigated changing participants' performance techniques on knee loading, and these have been restricted to landing tasks (10, 35). As more ACL injuries occur during sidestep cutting compared with landing, changing technique in this maneuver has greater potential to reduce ACL injury rates (9, 34).

Paragraph Number 3. Injuries to the ACL occur when the loads being applied to the ligament are larger than the ligament's capacity to sustain them. The ACL's primary function is to prevent anterior tibial translation, but cadaveric studies have shown that the ligament is also loaded by valgus and internal rotation moments at the knee (15, 25, 36). Previous laboratory studies have shown that when compared with running the knee has larger valgus and internal rotation moments during sidestep cutting, the authors suggesting that the valgus and internal rotation moments are major contributing factors to ACL injury (3, 4). Results from a prospective study of landing by Hewett and colleagues (17) supports this, finding females who had large peak valgus loads where at *a* greater risk of suffering an ACL injury. Video analyses in several sports have also reported that when the ACL ruptures during sidestep cutting the knee usually collapses into valgus (6, 9, 34). Recently it has been shown that the knee also gives way in internal rotation when the ACL ruptures during Australian Football games (9). Collectively, these results suggest that high valgus and internal rotation moments are a main cause of ACL injuries during side stepping and should be reduced if injury risk is to be lowered.

Paragraph Number 4. Cadaveric studies have found that the resultant strain experience at the ACL in knees for anterior forces, rotation and abduction/adduction moments is modified by the knee flexion angle (15, 25). In general terms as knee flexion angle increases there is a reduction in the resultant strain at the ACL. This appears to be reflected in vivo. Studies of actual injuries have found that athletes tend to have knee flexion angle of less than 30º at foot strike (9, 34). It would therefore appear that increasing knee angle may reduce the resultant load on the ACL for the same applied load at the knee therefore reducing the risk of injury.

Paragraph Number 5. Previous studies have indicated that there are differing techniques employed to perform a sidestep cut. Besier and colleagues (3, 4) identified two groupings within their subjects, one exhibiting mean valgus moments and one exhibiting mean varus moments during the weight acceptance phase of sidestep cutting. McLean and colleagues (30) observed inter-subject variability in knee angles during sidestep cutting, but did not report knee loads. It has been shown that by constraining arm movements during sidestep cutting, valgus loads at the knee are increased (8). Increased valgus loads have also been linked to increased hip flexion, hip internal rotation and knee abduction angles (28). However, no study has investigated the effect of imposing a range of different sidestep cutting techniques on knee loads. Therefore, the aim of this study was to identify if modifying sidestep cutting technique creates substantial and functionally important changes to knee loading. It was hypothesized that varus/valgus and internal/external rotation moments, and knee flexion angle, would be affected by changes in sidestep cutting technique.

Methods

Subjects

Paragraph Number 6. Fifteen healthy, male, experienced amateur team sport athletes, with no history of major lower limb injury volunteered to participate in this study (mean age 21.1 (±2.8) yr, height 182.5 (±7.1) cm, mass 73.3 (±10.4) kg). Experienced team sport (Australian football, rugby union and soccer) athletes were selected to ensure that they had sufficient skill in performing a sidestep cut. Our previous work comparing the differences between planned and unplanned sidestepping revealed effect sizes of about 0.8 (3). In the current study design to achieve similar effect sizes, which represented substantial functional differences, 7 subjects were required for an 80% power and alpha of $p<0.05$. For the same power and alpha we decided to recruit 15 subjects, which gave us the power to detect a smaller effect size of 0.65. All test procedures were approved by the Human Research Ethics Committee at the University of Western Australia (UWA), and prior to data collection written informed consent was obtained from all subjects.

Experimental Design

Paragraph Number 7. All trials were performed on a 20 m x 15 m runway and markers tracked by a 12 camera VICON MX motion analysis system operating at 250 Hz (VICON Peak, Oxford, UK), with ground reaction forces synchronously recorded at 2000 Hz from a 1.2 m x 1.2 m force plate (Advanced Mechanical Technology Inc., Watertown, USA). Subjects were asked to perform repeated trials of both normal and nine imposed sidestep cutting tasks during one testing session. Prior to commencing trials, subjects selected the preferred foot with which they would perform the sidestep cut. This foot was determined by subjects performing a sidestep cut with each leg and selecting their preferred side.

Paragraph Number 8. Subjects were required to perform five successful trials of each sidestep cut, which was to 45° (±5º) from the approach direction, with all subjects running at 4.5 (±0.2) m/s during the stride before the force plate. This speed was monitored using VICON Workstation (VICON Peak, Oxford, UK) to identify the average linear velocity of a marker on the left posterior superior iliac spine across the final approach stride. Cut angle was monitored through tape markings on the ground signifying 45±5º, with subjects required to land with their next foot contact within in these markings. All subjects performed their normal sidestep cut (NS), then sidestep cuts with nine different imposed techniques, categorized into four extreme postural groupings (Fig 1):

I) *Torso lean*: leaning in the same direction (T_{Same}) and leaning in the opposite direction ($T_{Opposite}$) to the direction of the sidestep cut;

II) *Knee*: knee straight ($K_{Straight}$) (as close to full extension as possible) and knee flexed (K_{Flexed}) (as flexed as possible);

III) *Frontal plane foot placement*: foot placed close to the body (F_{Close}) and foot placed away from the body (F_{Wide}); and

IV) *Transverse plane foot placement*: foot turned in (F_{In}) and foot turned out (F_{Out}).

In addition, we had one extra technique modification involving the trunk rotating in the opposite direction ($T_{Rotated}$), to which we found it was not possible to have a functional opposite for this posture. The NS was performed first followed by the imposed tasks presented in random order within the functional groupings.

Paragraph Number 9. The imposed postures were demonstrated to the subjects using a previously prepared video and standard instructions. A trial was then captured using a digital video camera and subjects were given both visual and auditory feedback on their performance. This step was repeated until the subject could successfully perform the imposed sidestep cut. This was assessed by same experimenters for each subject, using demonstration video as a reference. Once capable of performing the imposed sidestep subjects undertook the trials immediately. After undertaking the trials the subject was then trained and tested on the next imposed posture. This step was repeated until all imposed postures had been completed.

Paragraph Number 10. A trial was considered successful if the subject performed the required sidestep cut with the appropriate technique, achieved a cut angle of 45° ± 5 with the foot of the leg of interest landing on the force plate and did not target the force plate. Subjects were aware of the location of the force plate but to avoid targeting they were instructed to look ahead during their approach run. Targeting was identified by either a "stutter step" during approach or "reaching" towards the force plate with the last stride. To assist in this a run up marker was used to modify the approach distance to ensure the correct foot was striking the force plate.

Data Collection and Analysis

Paragraph Number 11. To facilitate the motion analysis, retro-reflective markers were affixed to the whole body to conform to requirements of the UWA Marker Set (5, 23) (Fig 2), which consisted of 50 markers placed on either bony landmarks or as part of three-marker clusters. Single markers were placed on the left and right forehead, left and right rear head, left and right acromion process, sternal notch, spinous process of C7 and T10, xiphoid process, left and right anterior superior iliac spines, left and right posterior superior iliac spines, left and right head of first and fifth metatarsal, left and right head of third metacarpal, and left and right calcaneus. Three-marker clusters were placed on the upper arm, forearm, thigh and leg and a two marker cluster on the dorsal surface of the hand. In addition, the ankle, wrist and shoulder joint centers were respectively defined using markers on the left and right medial and lateral malleoli, left and right radial and ulnar styloid processes and left and right anterior and posterior shoulder. These markers were removed during the dynamic trials. A 6 marker pointer was used to identify 3D location of the medial and lateral humeral epicondyles of both elbows, and medial and lateral femoral epicondyles of both legs (5). Functional knee and hip tasks were carried to identify knee joint and hip joint centers, as was a trial with the subject standing on a foot calibration rig (5). The latter trial was used to establish the position of the foot markers and to measure foot abduction/adduction and rear foot inversion/eversion angles (5).

Paragraph Number 12. Kinematic and inverse dynamic calculations were performed in VICON Workstation and Bodybuilder (VICON Peak, Oxford, UK) using the UWA Full Body Model, a combination of the UWA Upper and Lower Body Models (5, 23). Prior to modeling, both the ground reaction force and position data were filtered using a 4^{th} order 18 Hz zero-lag low-pass Butterworth filter, the filter frequency selected by performing a residual analysis and visual inspection of the data. The UWA Lower Body Model uses a functional method to identify both the knee joint and hip joint centers (5). The knee joint axis was located by calculating a mean helical axis using a custom MATLAB (Mathworks Inc., Natick, USA) program, with the knee center identified as the midpoint of the femoral epicondyles along this line (5). Spheres were fitted to each thigh marker trajectory to find a hip joint center relative to the pelvis anatomical coordinate system, constraining it to within a 100 mm cube around a regression calculated hip joint center (5). The foot coordinate system was established using the data from the foot calibration rig trial, which overcame errors in placing markers while incorporating the person's measured foot abduction/adduction and rear foot inversion/eversion angles (5). External moments were calculated with inverse dynamics (5, 20) using the body segment parameters calculated based on values in de Leva (11).

Paragraph Number 13. A custom MATLAB program was used to identify a weight acceptance phase during stance. This phase was from heel strike to the first trough in the unfiltered vertical ground reaction force (Fig 3). Although we have previously analyzed multiple phases of the sidestep cut, weight acceptance was selected as the sole phase to analyze in this study as the maximum magnitude valgus and internal rotation moments were found within this phase, indicating that this may be the period of high injury risk (Fig 4) (2-4).

Paragraph Number 14. Peak valgus (PV), peak internal rotation (PI) and mean flexion/extension (FE) moments were identified within the weight acceptance phase. Peak valgus and internal moments, rather than means, were chosen as peaks in both moments were exhibited during weight acceptance and large peaks could constitute dangerous loading patterns (Fig. 3). When analyzing the loads experienced in sidestep cutting other groups have also used peak valgus moments (17, 28). Mean flexion/extension moments were used as there was no definite peak within the weight acceptance phase. Knee flexion angle was identified at heel strike for all tasks. Joint angle data representing the imposed technique performed in the trial were determined and analyzed at heel strike to ensure that the subjects had successfully achieved each required technique. If this was not the case the trial was rejected. In all cases three or four trials for each technique were available for analysis. A subject average was calculated from these trials.

Paragraph Number 15. As we were interested in comparing the differences in knee moments and flexion angle between the extreme postures within each technique group and with the NS, a one way repeated measures ANOVA was performed on the following groupings: Torso lean: $T_{Opposite}$ -NS- T_{Same}, Knee: K_{Flexed} -NS- $K_{Straight}$, Transverse plane foot placement: F_{In} -NS- F_{Out}, and Frontal plane foot placement: F_{Wide} -NS- F_{Close}. Since the $T_{Rotated}$ did not have an extreme opposite posture it was only compared with NS using a paired t-test. For the paired t-test and the four ANOVAs we use an alpha level of $p < 0.05$ with no correction as all comparisons were specified a priori. However, in the post hoc comparisons within the four ANOVAs a Sidak correction applied to an original alpha level of $p < 0.05$, in preference to Bonferroni corrections which can be very conservative. To examine if relevant segment posture's angles were changed in the extreme postural groupings, we compared posture angles across all tasks using a repeated measure ANOVA for each variable using the same procedure described above. All statistical procedures were performed using SPSS 14.0 (SPSS Inc., Chicago, USA).

Results

Paragraph Number 16. There were significant differences in the relevant position data between each of the extreme postural groupings (Table 1). This indicates that the positions represent the extremes of a particular posture. In addition to this, four techniques also reported values significantly different to the NS: $T_{Opposite}$ had greater trunk lateral flexion away from the direction of sidestepping, $T_{Rotated}$ had greater trunk rotation in the opposite direction to the sidestep, K_{Flexed} had greater knee flexion, and F_{Wide} returned a greater foot distance from pelvis.

Paragraph Number 17. All tasks returned a mean FE moment with a value in the flexion range. The F_{Wide} condition returned a mean FE moment (-0.94 ± 0.36 $N \cdot m \cdot kg^{-1} \cdot m^{-1}$) with the highest flexion value (Fig 5). This was significantly greater than the F_{Close} (-0.72 ± 0.38

$N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$, p = 0.024) technique. The mean FE moment displayed during the NS (-0.78 ± 0.44 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$) was significantly greater than the F_{In} (-0.59± 0.37 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$, p = 0.021) and the mean FE moment displayed during the F_{In} was also significantly smaller than its pair task of F_{Out} (-112.96 ± 39.29 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$, p = 0.001). All other pairs produced moment values of similar magnitude except for T_{Same}, which tended to generate lower moments than during both the NS and $T_{Opposite}$.

Paragraph Number 18. The highest PV moment (Fig. 6) was again returned by the F_{Wide} condition (0.79 ± 0.38 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$), which was significantly higher than both NS (0.45 ± 0.32 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$, p = 0.000) and F_{Close} (0.51 ± 0.37 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$, p = 0.003) techniques. The PV moment generated during the $T_{Opposite}$ was significantly higher than its paired T_{Same} (0.65 ± 0.36 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$ vs 0.47 ± 0.36 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$, p = 0.030), and tended to be greater than the NS. All other pairs returned moment values of similar magnitude to each other.

Paragraph Number 19. Two techniques produced high PI moments in relation to the other tasks (Fig. 7). As with PV and mean FE, the F_{Wide} (-0.33 ± 0.23 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$) technique resulted in the highest PI, significantly greater than the NS (-0.19 ± 0.10 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$, p = 0.048). The NS also generated significantly lower PI moments than the $T_{Rotated}$ (-0.29 ± 0.10 $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$, p = 0.001). All other techniques returned PI moment values of similar magnitude.

Paragraph Number 20. As can be seen from Table 1 there was a significant difference in knee flexion angle between K_{Flexed} and $K_{Straight}$ (p = 0.000) as well as between K_{Flexed} and NS (p = 0.006). There were also significant larger knee flexion angle recorded in the $T_{Rotated}$ technique (23.6 ± 6.5º) compared to the NS condition (17.6 ± 5.5º, p = 0.010). The T_{Same} technique (22.3 ± 1.7º) retuned a knee angle that was significantly larger to both NS (p = 0.010) and $T_{Opposite}$ (18.2 ± 1.7º, p = 0.004). All other groupings returned similar values.

Discussion

Paragraph Number 21. The aim of this study was to identify if modifying sidestep cutting technique creates substantial and functionally important changes to knee loading. It has been shown that externally loading the knee with valgus and internal rotation moments results in high loading of the ACL (25). Two of the imposed postures F_{Wide} and $T_{Opposite}$ in the present study resulted in significantly higher peak valgus moments compared to their functional pair, with F_{Wide} also significantly higher than NS. In peak internal rotation moments there was no techniques that were significantly greater than its functional pair. However, F_{Wide} and $T_{Rotated}$ were significantly higher than NS. Markolf and colleagues (25) found that the combination of the two aforementioned loading directions significantly increased the strain being experienced by the ACL. Both peak moments occur in close to the same time point during the weight acceptance phase across the techniques (see fig 4), therefore, F_{Wide} is the technique most likely to endanger the ACL, as it returned significantly greater PV and PI moments.

Paragraph Number 22. For all three moments there was a general increase in magnitudes when compared to the normal sidestep. The average effect sizes for all moments were 0.48 for PV, 0.57 for PI and 0.45 for F. However, in the tasks where a significant difference was identified there was large effect size with mean value of 0.81. The smaller increases may not be “bad” in terms of ACL injury but rather a reflection of the subjects being inexperienced at the new task. A large significant difference between a pair of tasks indicates that a functionally important increase may have been caused by the body posture, and therefore the technique that produced the high loading should be avoided.

Paragraph Number 23. With reference to body posture three conditions were significantly different from NS, F_{Wide}, $T_{Opposite}$, and $T_{Rotated}$. The normal sidestep always occurs at some point between the two extreme postures, which are always significantly different from each other. Non- significant positional change may limit the ability to identify if technique changes modify the knee moments, but as all the extremes are significantly different it is possible to identify the moment changes from these positions.

Paragraph Number 24. There is currently some debate as to whether a high external flexion moment is good or bad in terms of ACL injury. A high external flexion moment, as exhibited in the F_{Wide} technique, indicates a high level of quadriceps activation to prevent the knee from flexing. Some groups argue that this increase in quadriceps activation is bad as it will increase anterior translation at the knee and therefore increase ACL load (14). The other argument is that an increase in quadriceps contraction will protect the ACL as the quadriceps have moment arms which provide support for the knee in varus/valgus and internal/external rotation (2, 24). In addition, McLean (27) showed that when modeling sidestep cuts, the level of quadriceps action causing anterior translation of the tibia was not sufficient to rupture the ACL. The stated reasons for this were that the quadriceps were not strong enough, and the action of quadriceps was counteracted by the action of the hamstrings and posteriorly directed forces on the tibia resulting from the deceleration experienced during the first half of stance. Nevertheless, when the anterior translation produced by the quadriceps is combined with valgus and internal rotation moments this is probably the loading condition that constitutes the greatest risk of non-contact ACL injury.

Paragraph Number 25. Knee flexion angles have been shown to alter the resultant ACL strain for the same load in cadaveric studies (15, 25). In the current study the significantly increased PI found for the $T_{Rotated}$ may not be as “bad” for the ACL as it first appears since the resultant load on the ligament may be lowered by the significant increase in knee flexion. However whether the 6º of increased knee flexion is sufficient to reduce ACL loads is unknown. The lateral hamstrings support of applied internal rotation loads at knee angles of less than 30º can reduce applied ACL load, therefore it would be expected that increased knee flexion will moderate the increased PI (26). However the loads occurring at the knee are in three dimensions. The resultant ACL load from a valgus load increases to 30º of knee flexion, even with muscular support (13, 21). Therefore while PV is of similar magnitude to NS (fig 6) the resultant load at the ACL caused by the PV moment may cancel out the reduction in PI due to the increased knee flexion. With the present position of the literature it is difficult to draw a conclusion as to the moderating impact of knee flexion.

Paragraph Number 26. Previous research investigating possible relationships between techniques and ACL injury has used video analyses of injuries occurring during games (6, 9, 34) . One major drawback in this type of analysis is there is no information about the loads being experienced at the knee, which can be assessed in laboratories studies. However, the limitation of laboratory analysis is that, while the knee loads can be calculated, they cannot be clearly linked to the actual injury. While a prospective studies laboratory such as Hewett's (17) allows for better links between the laboratory results and actual injury the positions achieved in the laboratory do not necessary reflect those which occur during the injury. Coupling the results from the laboratory studies and in-game injury analysis can overcome these limitations. Video analyses have suggested that an abducted hip, straight leg, foot rotated out, rotated torso and lateral torso flexion are often characteristic of non-contact ACL injuries (6, 14, 19, 34). Three of these postures are represented in the high loading techniques identified in this study: F_{Wide} – abducted hip, $T_{Opposite}$ – lateral torso flexion and $T_{Rotated}$ – rotated torso. During F_{Wide} the foot was also turned out more than in NS, with $T_{Rotated}$ also having more lateral flexion and hip abduction than NS (Table 2), consistent with the postures causing ACL injury suggested by video analyses. Therefore, the current work supports the previous video-analyses of ACL injury and provides the actual knee loads that may be related to the injury. It is recommended that sidestep cutting techniques that exhibit these postures should be avoided in order to reduce the risk of injury.

Paragraph Number 27. Athletes do not suffer an injury each time that they perform a sidestep cut, evident by the fact that no injuries were sustained during the present testing. This is the result of the external knee loads being supported by the muscles crossing the knee (2, 24). This study did not analyze the effect technique had on muscular support and is an area of future research. Previous work has found that when sidestep cutting tasks are performed under an unanticipated condition the loads experienced at the knee in both valgus and internal rotation increase significantly with possible compromised muscular support (2, 3). Unanticipated sidestep cuts are common during team sports, often to avoid a defender, a task which has been shown to change the kinematics of a planned sidestep cut (29). During the current protocol all sidestep cuts were performed in anticipated conditions. Should an individual perform an unanticipated sidestep cut with a F_{Wide} technique the knee loads experienced may be even higher and place the athlete at a high risk of injury. However, this notion requires further investigation.

Paragraph Number 28. Having identified sidestep cuts with techniques that may highly load the ACL the next step is to identify whether athletes can be trained to avoid using these techniques. If technique modification is successful in changing technique and reducing knee loads it can be added to current training protocols aimed at non-contact ACL injury reduction. However, in order to be accepted by the sporting community it would also need to be shown that the technique modification is not detrimental to the ability of an athlete to use their sidestep cut to avoid or intercept the opposing player. There also needs to be a long term prospective randomized control study similar to those performed by Caraffa (7), Hewett (16), and Myklebust (33) to identify whether technique changes aimed at reducing ACL injuries are successful or have any effect on other injuries. Athletes are unlikely to accept training that will increase their risk of another injury as there are other training protocols that have been shown to be effective at preventing ACL injuries and do not carry this risk (7, 16, 18, 33). If a technique modification study is unsuccessful it may also be appropriate to look at the ability to modify the technique of young, developing athletes. The motor patterns of adult, particularly elite, athletes may be harder to change, especially in unanticipated situations. This may not be true of younger, developing athletes.

Summary

Paragraph Number 29. In summary, sidestep cutting techniques have a significant effect on peak valgus, peak internal rotation and mean flexion/extension moments at the knee. With the identification of high risk techniques it be can speculated that it may be possible to develop training protocols that modify an athlete's sidestep cutting technique, specifically by bringing the foot to the midline and keeping the torso upright with no rotation, to reduce their knee loads and therefore *potentially* their risk of ACL injury.

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Figure Captions

Figure 1 Screen shots at heel strike from the videos used to demonstrate the imposed postures to subjects. The subject is stepping off the right foot and traveling left:. A) leaning in the opposite direction ($T_{Opposite}$); B) leaning in the same direction (T_{Same}); C) trunk rotating in the opposite direction ($T_{Rotated}$); D) knee straight ($K_{Straight}$); E) knee flexed (K_{Flexed}); F) foot placed close to the body (F_{Close}); G) foot placed away from the body (F_{Wide}); H) foot turned in (F_{In}); and I) foot turned out (F_{Out}).

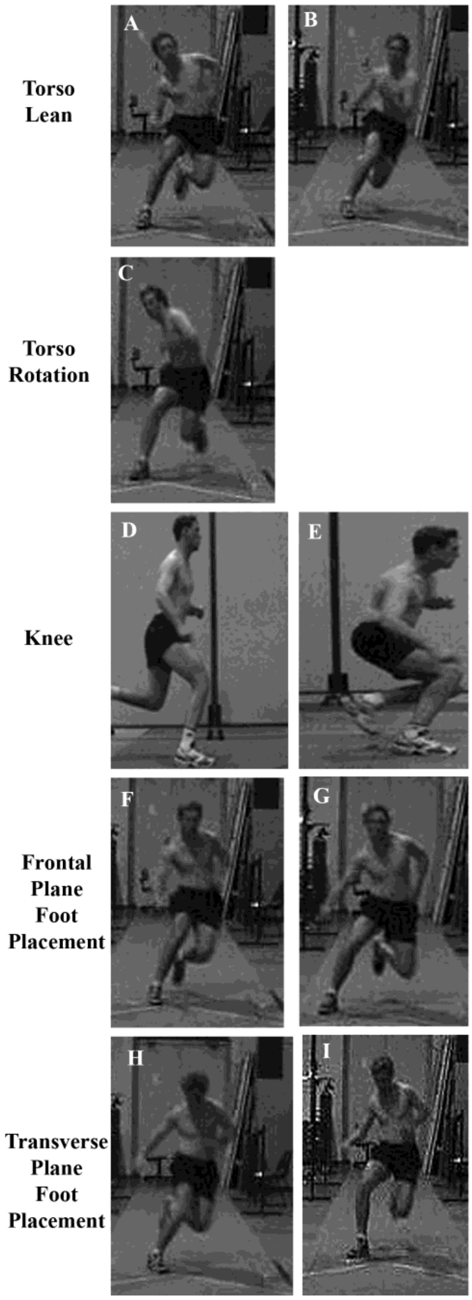

Figure 2 A participant showing the University of Western Australia (UWA) Full Body marker set.

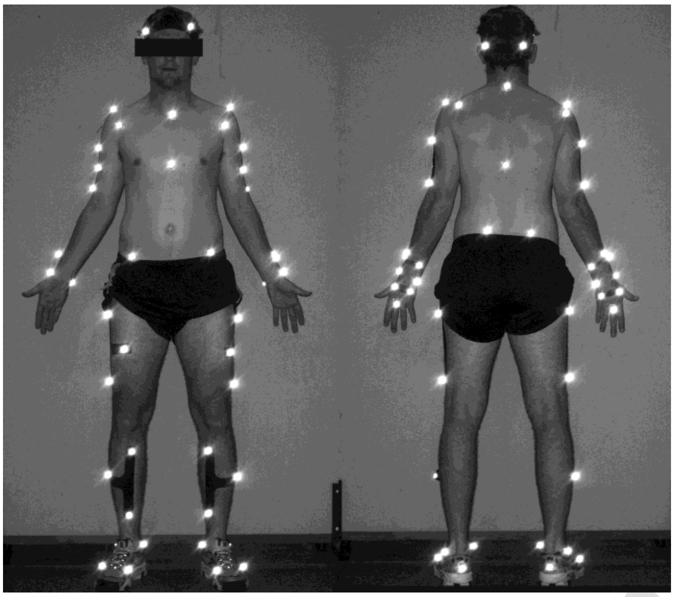

Figure 3 Vertical ground reaction force with the weight acceptance phase indicated.

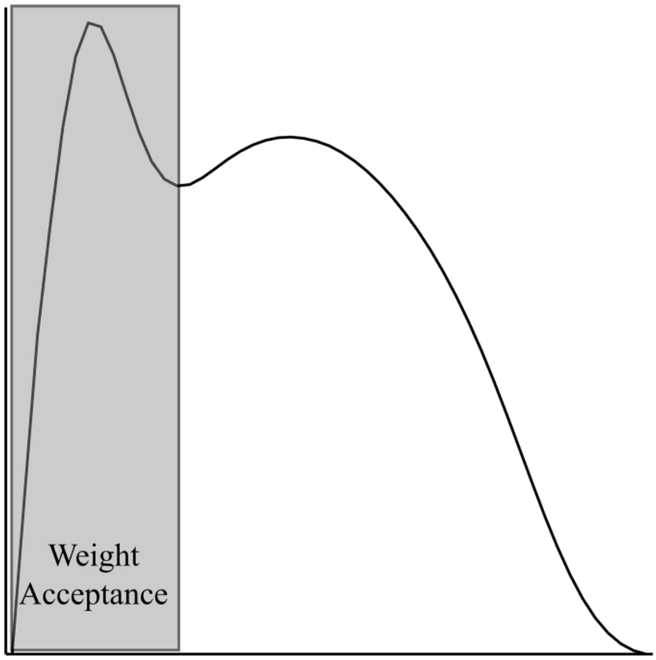

Figure 4 Average knee flexion/extension moment (A), varus/valgus moment (B) and internal/external rotation moment (C), averaged across all techniques. The circles indicate the peaks whereas the vertical line indicates the end of the weight acceptance phase.

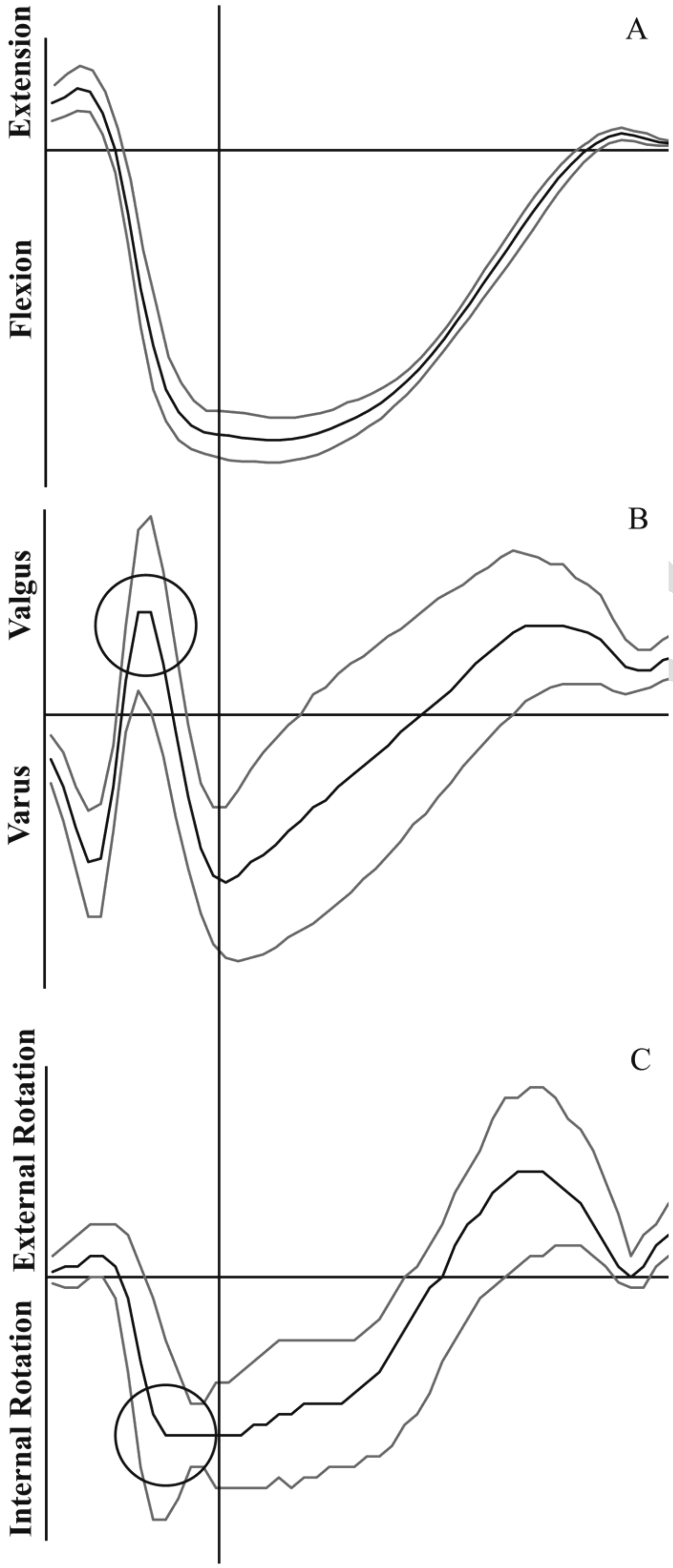

Figure 5 Mean flexion moment. Tasks with the same pattern were compared with each other and all tasks were compared to NS. *See Figure 1 for positions.* Tasks that have been linked with a line and an * are significantly different at $p < 0.05$.

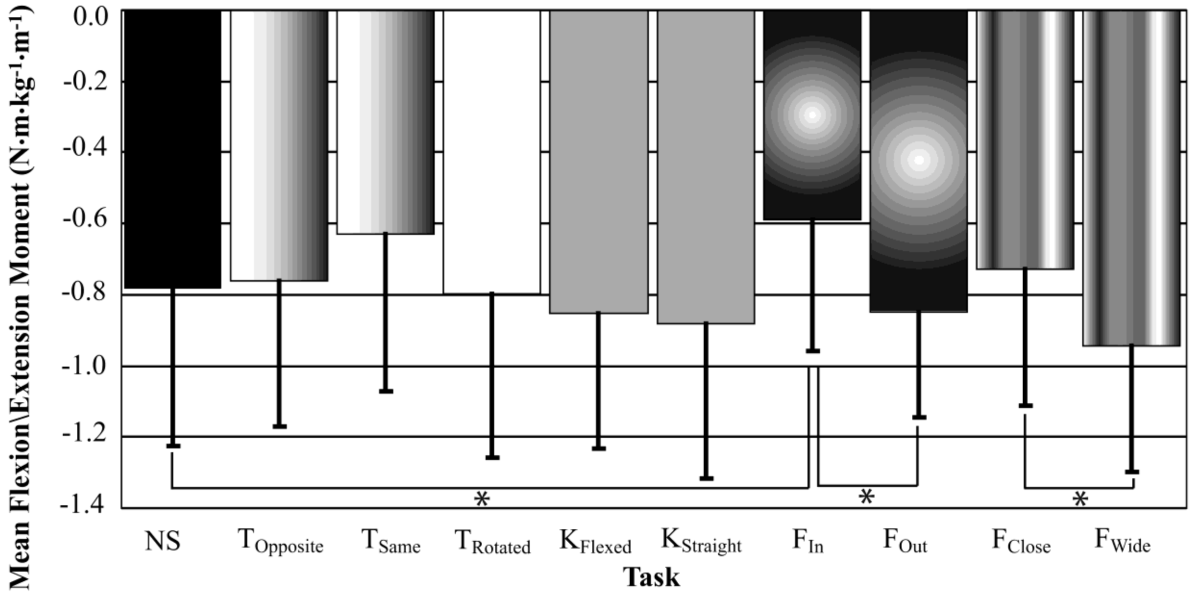

Figure 6 Peak valgus moment. Tasks with the same pattern were compared with each other and all tasks were compared to NS. *See Figure 1 for positions***.** Tasks that have been linked with a line and an * are significantly different at $p < 0.05$.

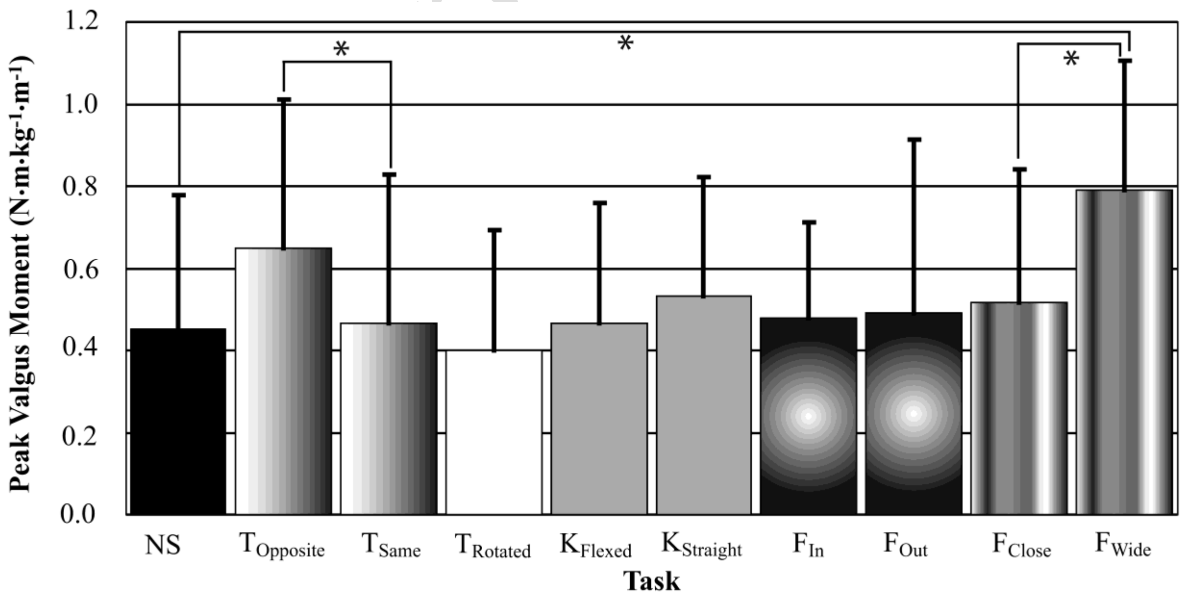

Figure 7 Peak internal rotation moment. Tasks with the same pattern were compared with each other and all tasks were compared to NS. *See Figure 1 for positions.* Tasks that have been linked with a line and an * are significantly different at $p < 0.05$.

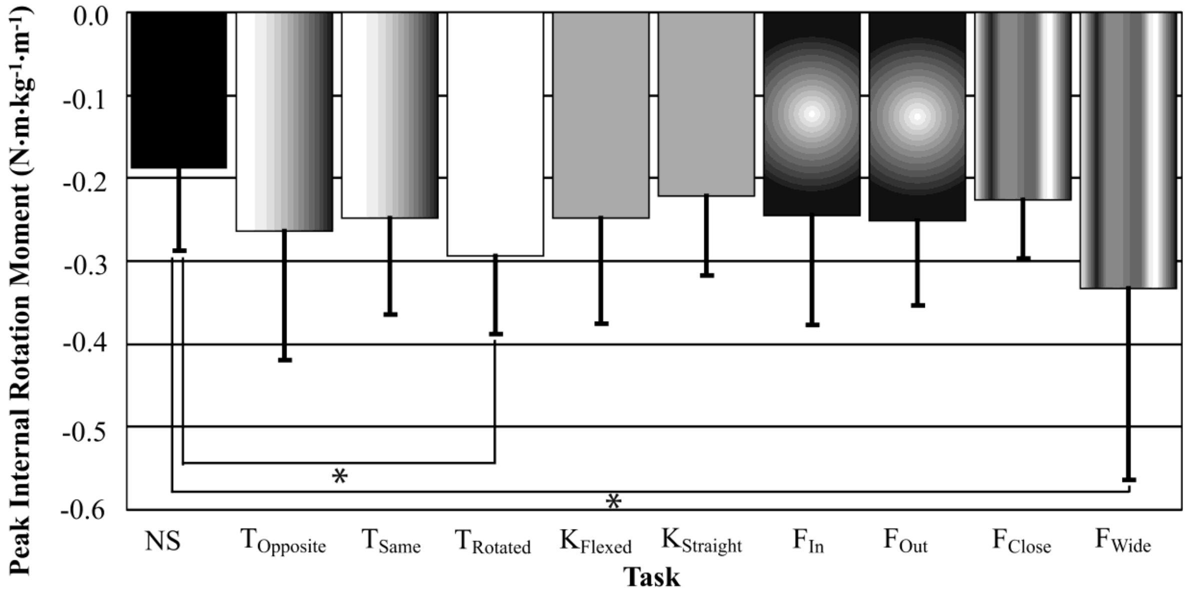

Table 1 Mean (SD) pertinent posture angles at heel strike for the different imposed postures. *Positions within the same column marked with an* * are a significantly different pair. *Positions marked with a* # indicate significant difference to NS (p < 05). Positive values indicate: Trunk Lateral Flexion – leaning right, Trunk Rotation – left shoulder back, Knee Angle – knee flexion, Toe Rotated In/Out – toe in.

	Trunk Lateral Flexion (º)	Trunk Rotation (º)	Knee Angle (º)	Foot Rotated In/Out (º)	Foot Distance from Pelvis (cm)
NS	7.7 (8.2)	-9.7 (8.7)	17.6 (5.5)	-10.4 (14.4)	34.4 (4.6)
$T_{Opposite}$	28.6 (8.2) * #				
T_{Same}	3.1 (9.8) *				
$T_{Rotated}$		-60.0 (8.5) #			
K_{Flexed}			22.7 (7.1) * #		
$K_{Straight}$			13.8 (6.7) *		
F_{In}				1.2 (10.9) *	
F_{Out}				-23.8 (6.3) *	
F_{Close}					30.7 (3.2) *
F_{Wide}					49.1 (4.1) * #

***Table 2** Mean (SD) posture angles representing common injury position at heel strike for techniques which retuned high knee loads and NS. Positive values indicate: Trunk Lateral Flexion – leaning right, Trunk Rotation – left shoulder back, Knee Angle – knee flexion, Hip Abduction/Adduction – adduction, Toe Rotated In/Out – toe in.*

	Trunk Lateral Flexion (º)	Trunk Rotation (º)	Hip Abduction/ Adduction (º)	Knee Angle (º)	Foot Rotated In/Out (º)
NS	7.7 (8.2)	-9.7 (8.7)	-10.6 (8.0)	17.6 (5.6)	-10.4 (14.4)
$T_{Opposite}$	28.6 (8.2)	-10.5 (9.6)	2.4 (9.3)	18.2 (6.7)	-9.9 (11.3)
$T_{Rotated}$	22.6 (9.0)	-60.5 (8.5)	-16.8 (10.6)	23.6 (6.5)	4.3 (9.0)
F_{Wide}	9.3 (7.9)	-6.9 (9.8)	-23.0 (15.2)	17.3 (6.7)	-22.9 (10.3)