MEASUREMENT OF HUMAN TEETH CHARACTERISTICS USING BITEPRINT®

SOFTWARE

By

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Dr Giles Oatley (Murdoch)

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Declaration

I declare that this thesis does not contain any material submitted previously for the award of any other degree or diploma at any university or other tertiary institution. Furthermore, to the best of my knowledge, it does not contain any material previously published or written by another individual, except where due reference has been made in the text. Finally, I declare that all reported experimentations performed in this research were carried out by myself, except that any contribution by others, with whom I have worked is explicitly acknowledged.

Signed: Andrea Chng
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Literature Review

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<table>
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<th>Definition</th>
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<tr>
<td>DNA</td>
<td>Deoxyribonucleic acid</td>
</tr>
<tr>
<td>ABFO</td>
<td>American Board of Forensic Odontology</td>
</tr>
<tr>
<td>NAS</td>
<td>The National Academy of Science</td>
</tr>
<tr>
<td>PCAST</td>
<td>The President’s Council of Advisors on Science and Technology</td>
</tr>
<tr>
<td>3D</td>
<td>3-Dimensional</td>
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<tr>
<td>2D</td>
<td>2-Dimensional</td>
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ABSTRACT

Bite mark impression evidence in criminal investigation may be of significance in allegations of child abuse and/or sexual assault. It enables the possible identification of the individual responsible for leaving the bite mark on the skin based on the teeth characteristics. Careful recording and documentation of the bite mark must be undertaken to maintain evidentiary value.

Bite mark analysis is often used to include or exclude a person of interest regarding the source of the bite mark on the alleged victim, this is done by comparing the individual’s dentition to the bite mark as it was based on the assumption that each individual’s dentition is unique, no two sets of dentition are the same. This assumption was before the NAS and PCAST reports rebated that the uniqueness of dentition has not been proved.

There are a number of manual methods available for forensic odontology to use for the analysis of bite mark. However, BitePrint© software will be the main focus of this study as it is able to work with both 2D or 3D images. This software was chosen as the bite mark will be imprinted onto dental wax sheets, which will then be photographed and uploaded into the software for analysis. Furthermore, this software is able to provide information of the dental parameter such as rotation, distance to the arch from the centre of the circumference, eccentricity, and intercanine distance. This information is of significant value in identifying the dentition responsible for the mark. However, the validation of this software has not yet been reported and there has only been one study done in the investigation of the application of BitePrint© to the identification of dentition, this literature review will explore the possibility of it so that it can become another tool for the forensic odontology to use.
1.0 INTRODUCTION: FORENSIC ODONTOLOGY AND BITE MARK ANALYSIS

The use of human dentition for identification dates as far back as 66 A.D at the times of the Roman Emperor Nero, where teeth was used to identify Lollia Paulina’s body\(^1\). In cases such as disaster victim identification (DVI) or when the face of the victim has been disfigured beyond recognition, the use of human dentition was able to identify the deceased individual. Each individual recorded dental data is characteristic of the individual’s dentition status revealing both the history of dental treatment and personal characteristics such as teeth pattern and medical conditions\(^2\). Dental treatment such as tooth extraction, restoration and shaping of teeth are permanent changes and are irreversible, thus assisting in the identification process.

Forensic odontology has been described as the “application of dental science to the administration of the law and the furtherance of justice”\(^3\). For over 100 years, forensic odonatologists have examined bite marks or patterned injuries in legal proceedings. A bite mark is “a mark caused by the teeth either alone or in combination with other mouth parts”\(^4\). Bite marks are considered as patterned injuries as it indicates the physical shape and characteristics of the dentition that caused it\(^5\). It can happen on living or non-living things. Bite marks can occur in multiple situations and are of significance in allegations of child abuse and/or sexual assault. Salivary DNA may also be recovered, but due to several reasons such as time of recovery, DNA degradation, cross-contamination, and insufficient DNA quantity, examiners are only left with the physical mark of the bite mark\(^6\).

Forensic odontology examination of teeth patterns on skin, begins with deciding whether the
injury was caused by human teeth before comparing the bite mark to a questioned dentition. Bite mark analysis is based on the assumption that each individual’s dentition is unique that no two dentitions are alike and the asserted uniqueness is transferred and recorded in the injury. However, NAS has superseded the report. Characteristics in a human bite mark is delivered as a class or an individual characteristic. Class characteristics includes feature, trait, or pattern that identifies a bite mark from other patterned injuries. In addition, it helps to discriminate whether the bite mark came from a human or other species. Whereas, individual characteristics is a feature, trait, or pattern that represents an individual difference rather than an expected finding within a defined group. There are two sub-categories under individual characteristics: arch and dental characteristics. Arch characteristics is the tooth arrangement within a bite mark such as a missing tooth or one or more diastemata may leave recognizable gaps in an arch in injury. Dental characteristics is the variation in an individual tooth. This includes chips, notches, or surface features in teeth or over-erupted or misplaced teeth which leaves evidence in the pattern of the injury. It was found that bite marks are unique to each person even in identical twins. Furthermore, in a research to determine the uniqueness of human dentition, monozygotic twins’ dental patterns were compared to each other. There was a significant difference between the twins in spite of similar developmental morphology of individual teeth. In addition, in another research, it was estimated that there were over two billion possibilities in the charting of adult dentition by the use of computer. A teeth impression can be compared against the bite mark data and matched for up to seventy-six comparison factors, including whorls, indentations, chips, abrasions, striations, distances between cuspids, tooth width and thickness, alignment and mouth arch.

In the famous bite mark case involving Ted Bundy, bite mark was utilized in solving the case.
Ted Bundy had assaulted and killed three women. There were no fingerprints left behind, and a murder weapon that could be found at the crime scene with DNA samples proved inconclusive. A bite mark was found on one of the woman’s buttocks which was a match to Ted Bundy’s dentition. The bite mark contained similar unique indentation mark, size of the teeth, sharpness factors of the bicuspid, laterals and incisors to the dental impression of Ted Bundy’s. However, bite mark analysis had also lead to the miscarriage of justice such as the Ray Krone case\textsuperscript{12,13}. The bite mark found on the victim’s body was found to be a match to the impression by Ray Krone. However, after more than ten years behind bars, DNA testing had shown that he was wrongly convicted. In addition, two Australian cases have rejected bite mark evidence as it was deemed unsafe and convictions overturned on appeal\textsuperscript{14}.

The basis of this literature review arises from the complications the comes along with bite mark analysis and why bite mark is placed under scrutiny by the NAS and PCAST report. Hence, the purpose of this literary review is to determine the most suitable method to address the issue and the limitations of this research. This literary review would also aid in the determination of the operational use of the BitePrint software that was created.

\section{DISCUSSION}

This section aims to critically review the literature that are currently available with regard to the mechanism of the bite mark and its effect on human’s skin and the complications with bite mark analysis, as well as the analytical techniques for analyzing bite mark patterns on skin.

\subsection{Bite Mark Mechanism}

When an individual bites their jaws tend to be wide open, this is referred to as wide biting. It
comprises of 2 opposite facing U-shaped arches that may be separated by open spaces or appear as a ring of marks\textsuperscript{15,16}. The upper teeth are used to stabilize the object while the lower teeth try to cut the object. The suction of the skin will create a negative pressure and the tongue thrust from the opposite direction. Therefore, there will be times that the palatal pattern could be found together with the appearance of the teeth edges as the palatal surface are often the first to be in contact with the object\textsuperscript{15,17,18}. As upper teeth and palatal surface have bigger surface area than the lower jaw, it is common to find more diffuse bruising related to the upper teeth. Whereas, the marks created by the lower jaw are more defined than those created by the upper arch\textsuperscript{5}. However, even though the lower arch creates a more defined mark than the upper arch, indentations from the upper arch are of significant importance in order to obtain information about the biter dentition\textsuperscript{17}. The mark produced when someone bites into something depends on several factors such as the force applied, the duration of biting, and the degree of movement between the skin and the teeth during biting\textsuperscript{4,17,19}. There are seven types of bite marks\textsuperscript{20,21,22}: 

- Haemorrhage: a small bleeding spot
- Abrasion: undamaging mark on the skin
- Contusion: ruptured blood vessel, bruise
- Laceration: punctured or torn skin
- Incision: near puncture of skin
- Avulsion: removal of skin
- Artifact: bitten-off piece of skin

These can be further classified by four types of impressions; clearly defined, obviously defined, quite noticeable or lacerated\textsuperscript{20,21,22,23}. 
2.2 Bite Mark Under Scrutiny

In 1986, ABFO had proposed to publish a scoring guide in an attempt to standardize bite mark analysis. However, due to a wide inter-examiner variability in scores in practice, the proposal was rejected. According to the ABFO guideline, forensic odontology has to determine if the bite mark is from a human first before proceeding to bite mark analysis\(^{24}\). If there are class and/or individual characteristics of human teeth, the examiner will deem it as inconclusive. As soon as the examiner consider it as human bite mark, they would be able to compare it to the questioned dentition. If there are class and/or individual characteristics that could have been created by the questioned dentition, then it cannot be excluded as the cause of the bite mark. However, if the examined dentition could not create the same class and/or individual characteristics, then it would be eliminated. If there are insufficient, missing, or incomplete information to conclude, the examiner would deem it as inconclusive.

![Figure 1: Flowchart of ABFO terms in relation to bite marks (image from [24]).](image-url)
Figure 2: Flow chart of bite mark analysis process (image from [25]).
To add on, Bowers and Pretty stated that the gross or class characteristics of teeth rather than the unique features are needed to positively identify an individual\textsuperscript{26}.

Even though, ABFO had developed a general guideline and methods that could be used to analyze bite mark, there is still no standardization on bite mark analysis, therefore placing it under scrutiny. The value and scientific validity of comparing and identifying bite marks has been an on-going dispute. In the NAS report, it was stated that the ABFO guideline did not
specify the criteria needed for using each method to determine if the bite mark can be related to the person’s dentition and with what degree of probability. Moreover, there are no research done on the accuracy of the analysis method. Even with the same guideline, a similar result could not be provided by experts and the same expert over time. Using controlled comparison studies, experts gave widely differing results and produced a high percentage of false positive matches of bite marks. Furthermore, as the guideline is not a necessity to be used in the criminal justice system, experts’ testimony is based on their experience and the method they had used for the analysis of bite mark. ABFO did not specify the minimum threshold for the type, quality, and a number of individual characteristics for evidentiary value. It was also stated in the NAS report that there is no evidence for the uniqueness of bite marks because a comprehensive study on a large population has not been undertaken to demonstrate what percentage of the population or subgroup of the population could have produced similar bite mark. Not only that, during investigations, police agencies would provide bite mark experts with the suspect’s dentition for comparison, it instils biases in them as there is a limited number of models for the expert to choose from in comparing the evidence. Bite mark experts have to make blind comparisons as they rarely have a number of models from other individuals in addition to those given to them for comparison with the bite mark. Moreover, the opinion from a second expert is not widely used, and the effect of distortion on different comparison techniques is not fully understood and thus has not been quantified. More research is needed to validate the necessary foundation of the science of bite mark comparison so that it is sufficient for a conclusive match.

This was further supported by the PCAST report. In the report, it was stated that bite mark analysis is not meeting the scientific standards for validity due to it being a subjective method.
and no appropriately designed black-box studies have been done. Therefore, providing conclusions that are not reproducible as there is no minimum threshold to meet to support a reliable conclusion which was stated earlier in the NAS report\textsuperscript{25}. As bite mark analysis methods were not conclusively proved through multiple, appropriately designed black-box studies, therefore the observed false-positive rates were above 10% or far above. There were several studies done in closed-set designs\textsuperscript{28}. However, it was not done appropriately. Hence the actual false positive rate was underestimated. This shows that examiners were not able to accurately pinpoint the source of the bite mark, and there was no consistent agreement between experts on the same bite mark if it is from a human dentition.

2.3 Factors Affecting the Appearance of Bite Marks

In this section, we will be discussing the variables affecting the appearance of bite marks on human skin and how these factors would affect the analysis of bite marks.

2.3.1 Primary Distortion

Primary distortion occurs at the time of biting. It is related to the medium being bitten and the bite dynamics.

2.3.1.1 Bite Medium

The medium, in this case, is skin. Skin is a poor registration material, and it is highly variable regarding anatomical location, underlying musculature or fat, curvature, and looseness or adherence to underlying tissues\textsuperscript{18}. Wrinkling of the skin in older age can also cause distortion\textsuperscript{29}. 
As skin is highly visco-elastic medium, primary distortion occurs during biting. When an individual bite another, the skin is capable of tissue distortion due to pressure, restoring back to its original appearance when the pressure is removed. Hence, during either the biting process or collection of evidence, stretching of the skin can occur. Those due to many variables, the skin might not accurately record the dentition to enable analysis.

Whittaker (1975) had conducted a study on the reliability of skin as a recording medium as compared to other material and on the accuracy of bite mark comparison. The study consists of eighty-four adults and two examiners; each participant gave upper and lower impression that were poured in dental stone and a bite into toughened model wax that had been mounted on curved wire mesh base with a radius similar to an upper arm. Each wax bite was photographed with a scale, with the impression taken as study model for bite marks. Twenty-four participants were tasked with biting into pig skin wrapped over a rubber cylinder with a
radius similar to an upper arm. Pig skin was found to be comparable to human skin. These bites were treated the same way as the model wax except that photographs and impressions were taken at one hour and twenty-four hours. Examiners were tasked with matching the wax bites and stone models of the wax bites with the original dental study model and photographs of the wax bites with the photographs of the original dental study models. Examiners compared the stone model and bites by either trying to fit the dental study models into the wax bites or visually comparing the two stone models. The photographs were compared by measurement of the models and a visual comparison only. Both examiners were able to correctly match 98.8% of the wax bites and stone models of the wax bites with the original dental study models. Whereas, the accuracy of matching of the photographs of the wax bites and the study models were 96.5% and 95.5% and visual only comparison were 68% and 67%. For the bite mark on pig skin, results were pretty similar for the photographs taken immediately after biting. However, the results for the photographs taken after an hour and twenty-four hours were only 35% and 16% respectively. Visual only comparison made after twenty-four hours had a 9% accuracy. Thus, visual is the least accurate method. This study demonstrated that skin is a poor medium for bite mark comparisons as compared to wax.

2.3.1.2 Bite Dynamics

There are variations in bite marks appearance even by the same dentition due it being proportional to the degree of movement; dynamic distortion. Dynamic distortion composed of multiple component movements by the biter and/or the victim during contact between the dentition and the skin\(^{18,30}\). Other factors include the amount and type of force applied; biting, sucking, or tongue trusting, the length of time the force was applied, and the direction of the bite. The mechanical properties of skin can modify the appearance of bite marks such as site
variations and directional variations\textsuperscript{21}. Site variations vary from site to site, depending on the location of the bite mark; the skin found on the breast are softer than those of the back due to the differences between the binding of the skin and the subcutaneous tissue. The amount of tissue available for biting also lead to tissue distortion, as it changes dimensional changes in the skin due to the “tenting” of tissue in the mouth.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{tenting.png}
\caption{“Tenting” of tissue in the mouth (image taken from [31]).}
\end{figure}

Directional variations are due to the Langer’s line; the preexisting tension lines (elastic fibres of the dermis) in the skin. An alteration in the region of high extensibility displays the most noticeable directional differences. Directional variations alter with movements and changes in body position and these cause distortions in bite marks.

\subsection{2.3.2 Secondary Distortion}

Secondary distortion happens after a bite has been placed or during the examination and recording of the bite mark. NAS report (2009) had reported that it was due to the elasticity,
unevenness of the surface bite and subsequent swelling and healing of the skin\textsuperscript{27}. There are three main components for secondary distortion: time-related, posture and photographic distortion\textsuperscript{30}.

\subsection*{2.3.2.1 Time-related}

Time-related distortion is related to the bite changing over time such as tissues changes due to the healing of laceration causes a modification in the dimensions and detail of the bite and part of the bruise might diffuse to a different site, therefore, giving a different shape. After biting, oedematous will take place due to the skin reaction to the trauma, causing the area to stiffen thus reducing distortion as it is stable. However, over time the stiffening effect will reduce as the fluids are resorbed. This will create distortion, and the appearance of the bite mark is highly likely to change.

\subsection*{2.3.2.2 Posture and Photographic Distortion}

Posture distortion is in relation to the bite mark being viewed or recorded in a different position from when the tissue was being bitten. The variations in body position and anatomical location can affect the degree of posture distortion. Sheasby and Macdonald\textsuperscript{30} had reported that it is essential to try and reconstruct the victim’s body at the time of biting as this will minimize posture distortion. This was justified by Babenel and Evans\textsuperscript{33}, as it was stated that movement would alter with the directional variations or tension lines. The findings by Devore (1971) further supports that the exact position of the body must be known for comparative analysis to be used as it was shown that there was a change in the stamp after subjects were given instructions to change position. However, it is not always possible to...
know the exact position of the body during biting\textsuperscript{30,34}. Therefore, photographs of the bite marks should be taken in a wide range of positional possibilities\textsuperscript{30}.

\textbf{Figure 6:} Stamp on a flexed thigh (image taken from [45]).
Figure 7: Stamp on the thigh was distorted when the thigh was extended (image was taken from [45]).

2.3.2.3 Photographic

Photographic distortion is caused during the recording of bite mark by the photographic method. This is influenced by the angle of the film to the mark and the body curvature. The ideal photographic angle is 90°, the camera must be perpendicular to the center of the bite mark to create a parallelism between the film plane and the bite mark plane. To minimize photographic distortion, a bite mark standard references scale (ABFO no.2) which contains a circular scale on it was created by the ABFO.

There was no further work done on the quantification of bite mark distortion on human skin due to several reasons: expensive, ethical reviews due to it involving human subjects, and skills are not normally held by forensic dentists such that other skill experts are required.
According to Blackwell et al. (2007), biting is a 3D event as it involves the curvature of the skin, shape of the biting dentition, and the depth of the injury. Therefore, 3D technique should be used to analysis bite mark. This was also supported by Maloth and Ganapathy\textsuperscript{35}.

### 2.4 Bite Mark Analysis

In this section, we will be discussing about the several techniques that could be used to generate overlays and the pros and cons of these techniques. It is important to take note that Ramos et al.\textsuperscript{36} has stated that indentations of the tooth marks that are left on the skin increase the probability of matching the dentition responsible for the bite mark. We must also keep in mind that studies had been done to determine the accuracy of the overlays. Yet, it does not address the application of these overlays to the successful identification of a biter as commented by Pretty\textsuperscript{42}.

<table>
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<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Computer based method</td>
</tr>
<tr>
<td>2</td>
<td>Xerographic method</td>
<td>Xerographic method</td>
</tr>
<tr>
<td>3</td>
<td>Hand tracing from wax method</td>
<td>Radiopaque wax method</td>
</tr>
<tr>
<td>4</td>
<td>Hand tracing from study cast</td>
<td>Hand tracing from wax method</td>
</tr>
<tr>
<td>5</td>
<td>Radiopaque wax method</td>
<td>Hand tracing from study cast</td>
</tr>
</tbody>
</table>

**Figure 8:** Ranking of bite mark analysis techniques for area and rotation (image taken from [35]).
2.4.1 2D Techniques

There are five 2D techniques to analysis bite mark; hand tracing from dental study casts, hand tracing from wax impressions, radiopaque wax impression, xerographic and computer-assisted method\textsuperscript{35,37,38}.

Hand tracing from study casts is done by placing a transparent sheet over the biting surfaces of each set of upper and lower study casts and hand tracing using a soft fine tipped felt pen of the perimeter of the biting surface of the anterior teeth\textsuperscript{35}. The bite mark expert has to observe the size, shape, and anatomical position of each tooth through the clear film and the adds the laterality indicator\textsuperscript{37}.

Hand tracing from wax impression method is similar to the hand tracing from study casts method. Before tracing onto a transparent sheet, a shallow impression of the biting surfaces of the six uppers and lower anterior teeth are created by pressing the study cast into a single wafer of modelling wax sheet\textsuperscript{35}.

Radiopaque wax impression method is done by tracing the radiographic image onto a transparent sheet and adding laterality markers\textsuperscript{35}. The shallow impressions of the biting surfaces of anterior teeth were produced as illustrated in hand tracing from wax impression method. Subsequently, the size, shape, and anatomical position of the biting surfaces of the anterior teeth are recorded by the residual metal powder after adding a small quantity of silver amalgam powder to the impression and allowing it to evaporate. The radiographic image was produced using a dental x-ray machine. Once the film is processed, the bite marks
would show up as white teeth marks in a dark black background.

Xerography overlay method is done by making a life-size image of the biting edges of teeth from the study casts using a photocopier. A radiograph view-box was used to illuminate the print-outs, and the overlay was created by hand tracing the incisal margins onto a transparent film\textsuperscript{22}. This is referred to as the “hollow-volume tracking”. Some degree of operator’s ability is still involved as it requires a certain level of expertise to produce the overlay. Xerography method was found to be more precise than the conventional hand-tracing on plastic films placed over dental casts.

However, according to Santhosh and Jagannathan\textsuperscript{9}, Sweet and Bowers\textsuperscript{37}, and Meng et al.\textsuperscript{17}, hand tracing methods are found to be highly subjective and irreproducible as it can be easily manipulated. It was recommended that hand tracing methods should not be used for analyzing bite mark as it compromises on the precision and accuracy. Moreover, Sweet and Bowers\textsuperscript{37} results had shown that there is instrumentation error in the xerographic method. This is due to the static charge on the glass platen which attracts the photocopying ink hence producing a replicate image which is larger in area than the original despite corrections done by using a scale on the glass platen\textsuperscript{37}.

\textbf{2.4.1.5 Computer-Assisted Overlay}

The use of computer assisted overlay allows examiners to have the ability to add text to an image, work at higher magnifications, enhance the images for better viewing, resizing of images, detect and make correction of angular distortion present in original photograph of the bite mark, reliable fabrication of an overlay of a suspect, make comparison using
superimposition or side by side comparison, standardizing of the methodology and the ease at which others can view the process\textsuperscript{39}. Digitally photographed images can be viewed immediately to check if retakes are needed.

However, there are disadvantages of using a computer assisted overlay are cost and operators must have the knowledge and skills to use the software. The case notes should contain each step taken in detail such that another trained individual is able to repeat and produce the same results. Equipment must be calibrated at all times, and it must be recorded for recording and verification purposes. Imaging software programs can be used in such a way that the actual image is changed and the information is missing or lost from the image. However this is overcome by the use of history palette.

Computer-assisted overlay method uses 2D digital SLR cameras and computer image processing software such as ImageJ or Adobe Photoshop\textsuperscript{®} “magic wand” tool. A hollow-volume tracing was done from the mask which was created from the selected areas of the biter’s dental casts\textsuperscript{17}. Computer-assisted overlay method was found to be the most accurate method as commented by Sweet and Bowers\textsuperscript{37}, Meng et al.\textsuperscript{17}, McNamee et al.\textsuperscript{40}, and Stavrianos et al.\textsuperscript{41}. There is no subjective bias from the operator as the software Adobe Photoshop CS6 selects the biting edges. However, Meng et al.\textsuperscript{17} also stated that the biting edge selection by Adobe Photoshop CS6 is based on the clarity of the image and the surrounding light during the scanning. Therefore, the accuracy of the biting edges selection depends on how clear the image is.
2.4.2.1 3D Techniques

DentalPrint© is a software package that was created by Martin-de las Heras et al.43. 3D contact-type scanner was used to scan the dental casts, the images were imported into the software and processed. Comparison overlays from 3D images of the dental casts were obtained in 3 steps as illustrated by Martin-de las Heras36:

- Teeth involved in bite mark were identified.
- A contact plan was created from the three highest points detected in areas defined in the 3D images of the dental casts.
- Biting edges were obtained with DentalPrint©, which allows the contact plane to extend deep into the teeth.

The perimeter of the suspect’s biting edges can be printed onto a transparent acetate film or converted into a bmp file. Maloth and Ganapathy35 had commented that it is the most accurate method as it is full automatic, therefore, avoiding observer bias and it is impossible for third parties to manipulate or alter the 3D images. Martin-de las Heras et al.44 had researched DentalPrint© software to determine values of intra and inter-examiner reliability, sensitivity, specificity, and validity while comparing it to Adobe® Photoshop® software. It was shown that bite mark analysis with DentalPrint© is an accurate method44. Furthermore, they also found that the best results were obtained with the usage of DentalPrint© software to generate comparison overlays. However, they had also included that 2D is more affordable and easily accessible than 3D method.

2.4.3 BitePrint© software

BitePrint© was developed by Ramos et al.36. It is based on bite mark photographs of the
victim’s skin from real forensic cases with the court’s decision as the gold standard. Johansen and Bower method\(^3\) was used to correct the photographic distortion of the bite marks, and ABFO scale no.2 was used as the coordinate system. The software yields objective and quantified parameters of significance for forensic identification of bite marks, including intercanine distance, rotation, eccentricity, angular position, and position to the arch of each tooth mark. The software can also work with images of biting edges developed from 3D images of dental casts obtained from DentalPrint\(^\circ\); this helps to retain the dynamic characteristics of the biting. BitePrint\(^\circ\) software is a less subjective analysis as it is semi-automatic, thus reducing the participation of observer in the process. However, Ramos et al.\(^3\) also mentioned that expert is still involved in drawing of the initial ellipse and the labelling of the tooth types in the bite mark. Furthermore, bite mark analysis can be affected by using 2D technology as the capturing of tooth marks are less accurate. 2D technology will create distortion and errors that would negatively affect the digital measurement process\(^3\). However, as this is a software that was recently created, further research is required to validate this new method. Ramos et al.\(^3\) commented that experimental trials are needed to compare bite mark bruises from photographs against dental casts of potential aggressors by using a large dental cast database for searches and comparisons and if the dental parameters that were obtained after image processing are sufficiently representative of dentition to allow its proper identification\(^3\).

3.0 EXPERIMENTAL DESIGN ELEMENTS

In this section, we will be talking about the materials used in this study and why these materials were chosen compared to the others.
3.1 Alginate Impression

The alginate dental impression forms a negative mould of individual’s dentition. The impression material used in this study will be alginate; Identic Dust Free R/set Single Unit (Matrix Dental Services, Bayswater North, Victoria, Australia). This brand was chosen as it is easy mixing, excellent stone surface, smoothness and fine detail. Furthermore, it is for single use. It contains a pre-measured volume of dental alginate for a single impression, and water measurement is incorporated as part of the packaging. Thus, ensuring a consistent mix every time. However, this item only has 100 hours of stability, meaning that casting of the impression must be done within the 100 hours or else some details might be lost which will make the study less accurate.

There are four main impression materials that are usually used in dentistry and it can be categorized into rigid (zinc oxide eugenol and impression compound) or elastic impression materials (alginate and silicone). Rigid materials are usually used for the impressions of edentulous arches only as it does not flow well and is unable to record the fine detail. It is not able to reproduce undercuts, so it is not suitable for partial denture impressions, and it contains eugenol which some people might be sensitive to.

Alginate was picked as it is one of the materials approved by the American Dental Association and it is the most frequently used dental material. It is simple to use and cost-effective. Alginate has the ability of good surface detail. It is also hydrophilic, thus making it a good and accurate impression even in the presence of saliva or blood. It has a low wetting angle thus the full arch impressions are easily captured. It can be easily removed. The working time for
alginate is very dependent on the temperature of the water, and it is available as standard or fast setting. However, there are disadvantages of using alginate such as poor dimensional stability, messy to work with, excess water gain/loss and lead to swelling/shrinkage respectively, it can distort easily, and it has to be cast up as soon as possible to avoid shrinkage. According to the Dental Nurse Network (2018), silicone is the most dimensionally stable out of all the materials and will retain their shape even after being left for a long period. However, it requires a dry environment and little to no saliva to work optimally.

3.2 Dental Stone

Hydrocal®105 yellow dental stone (Adelaide Moulding & Casting Supplies, Somerton Park, South Australia, Australia) will be used for casting. This material incorporates quickly and has a high strength within an hour after set. It has 6000psi dry compressive strength after 24 hours and will expand by 0.2%.

Casting provides a positive replica of the dentition. When the dental stone hardens, it will form a permanent cast providing a mirror image of the impression. The cast may be slightly bigger than the original dentition due to the dental stone expanding by 0.2%. This has to be kept in mind. There are four types of gypsum products; type I (impression plaster), type II (dental plaster), type III (dental stone), type IV (improved dental stone or die stone or high strength stone), and type V (dental stone, high strength, high expansion).

Type I is usually used to make a primary impression of the edentulous oral cavity in complete denture fabrication.

Type II is used for making study cast or primary cast. It sets fast, but there is enough time for manipulation. It is a hard and strong mass after setting, and it neither expand nor contracts by a lot. It is strong enough to undergo molding and curing procedures.

Type III is usually used for making casts that are for processing denture as it has the strength and hardness and denture can be easily removed after processing.

Type IV must be hard, abrasion resistance, strength and minimal setting expansion. The hard surface is needed as the cavity preparation is filled with wax that is carved flush with the margins of the die.

Type V dental stone possesses higher compressive strength than that of type IV.

Type III (dental stone) are commonly used for casting even though it is less strong than Type IV and it also expands a little. However, it has a relatively high strength, its surface reproduction is nearly as good as those of higher strength stone, and it cost less than the higher strength items. Whereas, Type II has the highest setting expansion and is weaker when compared to Type III and Type IV. It is usually used to stabilize master casts in position to articulators.50

3.3 BitePrint© Software

BitePrint© software was chosen to analysis the bite marks as hand tracing methods were
found to be highly subjective and not reproducible, therefore, it will affect the accuracy and precision of the result. Computer-assisted methods were shown to be the “gold standard”. Hence, the computer-assisted method was chosen for this study.

As stated earlier, BitePrint© software is a new software package that was developed in 2017. It has not been validated yet which will be done in this study. As the software will be based on bite mark photographs of the victim’s skin from real forensic cases with the court’s decision as it is the gold standard. There might be photographic distortion, which could be overcome by correcting the distortion using the Johansen and Bower method.

It would be best to work with the images of biting edges from the 3D images of dental casts from DentalPrint© as it helps to retain the dynamic characteristics of the biting. Unlike 2D methods, which will create distortion and errors, therefore, affecting the accuracy of the capturing of tooth marks.

4.0 EXPERIMENTAL AIMS AND HYPOTHESIS

From the research presented in this literature review, it has been demonstrated that the usage of 2D or 3D technique could affect the results from BitePrint© software. Thus, the experiment dictated by this literature review aims to undertake a pilot study to test the validity of the BitePrint© software to produce reliable and consistent results.

Research aims and objectives:

It is to investigate the operational use of a recently developed BitePrint© software. This is
done by analyzing the bite mark images in the software which will computes the dental parameters. These measurements will be taken for reproducibility and repeatability testing. The calculated values will be able to indicate if the software is able to produce reliable and consistent results.

**Objectives:**

1. Validation of the BitePrint© software.
2. To determine BitePrint© software could be another tool for the forensic odontology to use.

**5.0 Conclusion**

In conclusion, bite mark analysis ultimately depends on the appearance of the bite mark on the skin. There are many variables that could affect the appearance of the bite mark which will in turn increase or decrease the accuracy of the bite mark analysis. Furthermore, the technique used could also affect its accuracy. BitePrint© software had shown to have the potential to be an accurate method to analysis bite mark. However, it has not yet been validated. However, as this study is not done on human skin, the influences of skin tension, anatomical location of the bite injury or skin movement during the bite must be considered when using this method for bite mark analysis on human skin. As this study is testing the validity of the method on standardized templates. It could be applied to skin for testing in the future. Furthermore, as the guideline for bite mark analysis is very general, it is still under scrutiny as it is not specific.
6.0 REFERENCES


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Part Two

Manuscript

Measurement of Human Teeth Characteristics using BitePrint© Software
Measurement of Human Teeth Characteristics using BitePrint© Software

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ABSTRACT

Bite mark analysis aids in providing information and identifying the dentition that had left the bite mark behind. However, it has been brought under close examination due to multiple issues with the guidelines set by the American Board of Forensic Odontology (ABFO) and the methods available for bite mark analysis. Even though bite mark evidence is admissible in court, it has led to many wrongful arrests or convictions due to the complications arising from it. This study investigates the reproducibility and repeatability of BitePrint© software, which was recently developed in 2017. In this study, six dental casts were used to apply to wax under controlled conditions. The width of each tooth from each dental cast will be measured against the measurements obtained from the software. Statistical analysis of the results demonstrated that the software is reliable. However, the results had shown that the software has low reproducibility rate meaning that it does not produce consistent results. This might be due to only one aspect of the parameter which was the width of the teeth being tested in this study. Other dental parameters could be taken into considerations for further studies.

Keywords: Bite mark analysis, BitePrint software, Dental parameters, Forensic Odontology, Forensic science
INTRODUCTION

Forensic odontology has been described as the ‘application of dental science to the administration of the law and the furtherance of justice’\(^1\). A bite mark is ‘a mark caused by the teeth either alone or in combination with other mouth parts’\(^2\). Bite marks represent the physical shape and characteristics of the dentition that caused it, hence it is a patterned injury\(^3\). It can occur in multiple situations such as assaults, child abuse and/or sexual assault. In such cases, salivary DNA can be recovered from the mark to identify the source. However, at times due to several reasons such as DNA degradation, cross-contamination, and/or insufficient quantity, examiners only have the physical mark of the bite mark to examination\(^4\).

The current method that is commonly used by forensic odontology for bite mark analysis is transparent overlay however, this is generally only good for exclusion. Furthermore, it was stated in the PCAST\(^6\) and NAS\(^5\) reports that there has been no research undertaken to investigate the accuracy of the analysis methods\(^5,6\) and reports could conclude that bite mark analysis was found to be a subjective method due to the influence of the examiner’s judgement on the results, therefore providing conclusions that are not repeatable\(^7,8,9\).

BitePrint\(^\circ\) was recently developed by Ramos et al.\(^10\) in 2017. It uses the American Board of Forensic Odontotology (ABFO) scale no.2\(^11\) as the coordinate system. The software computes the dental parameters for forensic identification of bite marks such as distance to the arch, rotation, angular position, eccentricity, and intercanine distance. It can work with 2D and 3D images. Furthermore, it is a semi-automatic software, therefore, making it less subjective as it reduces the observer’s input. However, the operator is still involved in drawing of the initial ellipse and labelling of the tooth types in the bite mark. As this software is considered new in
the forensic odontology’s field, further research into the validation of this method is needed. There has been only one study conducted with this software.

This study aims to investigate into the repeatability and reproducibility of the BitePrint© software. Controlled variables such as dental casts used and dental wax sheets would indicate if the measurements obtained from the software are reliable and accurate. As there are multiple issues with teeth impression evidence, this is an assessment of BitePrint© software as a more robust method.

**MATERIALS AND METHOD**

The experimental setup consisted of 5 different dental casts (model no: 1 (top), 2 (bottom), 3 (bottom), 7 (top), and 9 (bottom)), an ABFO No. 2 ruler (Crimescene - #X000QVWLN3), dental wax sheets (Ivoclar Vivadent – Type 4 base plate wax), a heater (Techne – Hybridiser HB-1D), a digital calliper (Linear Tools 2012 - #4360896, 0 – 150mm digital calliper), BitePrint© software, a thermometer (Rowe Scientific Pty Ltd – In/Out Thermo), a timer, a water bath, a DSLR camera (Nikon D5500), micro lens, a standard tripod stand, and using a PC with Intel® Core™ i7-4700MQ CPU 2.40GHz, 8192MB of RAM and Windows 10 operating system.

**Dental Wax Sheets Preparation**

Two dental wax sheets were placed into a water bath heated up to 30°C. After 10 seconds, the dental wax sheets were removed and compressed together to produce a thickness suitable for receipt of dental impressions. This was repeated for each set of dental casts. The stacked wax sheets were then cut into three equal parts and labelled with the model no.,
Impression Preparation

The cut stacked wax sheets were placed inside the heated oven set at approximately 45°C. After 90 seconds, the softened wax sheets were removed, and pressure was applied to a dental cast to create a 2mm depth onto the wax sheets to create an impression of a minimum of the front four teeth. The top dental cast was parallel to the surface. The steps from putting cut stacked wax sheets were repeated for each dental casts #1, 2, 3, 7, and 9 in triplicate.

The camera was mounted on a standard tripod stand with 60mm micro lens. The ABFO no. 2 ruler was placed beside the impression on the wax sheet before it was photographed. The circles on the ABFO no.2 ruler were aligned to the camera to prevent photography distortion.

The measurements for the width of the front four tooth of each dental cast were manually measured with a digital calliper for comparisons with the values obtained from BitePrint© software later on.

Testing and Measurement Procedures

The images were processed with a basic windows editor to enhance the clarity of it before processing on the BitePrint© software.
Figure 1. Windows photo editor used to enhance the clarity of the impressions on the dental wax sheets.

Figures 2 & 3. The before and after of the image

The edited images were uploaded onto the BitePrint© software for processing. The ABFO no.2 ruler was used as the coordinate system. The two axes (mesiodistal length and buccolingual width) were drawn for each of the four tooth marks. The software automatically adjusted the initial ellipse to the tooth mark by measuring the colour inside the ellipse and
its’ nearest surrounding area. The software can automatically adjust the circumference that best fits the four calculated ellipses. A point was then placed between the two central marks, and the software automatically draws a line from this point to the centre of the circumference. The software automatically computes the width of the marks.

**Figure 4.** BitePrint© software automatically adjusted the circumference that best fits the four calculated ellipses. It also automatically draws a line to the centre of the circumference after inputting the point between the two central marks.

The calculated parameters were saved for further comparisons. The values obtained from both the digital calliper and BitePrint© software were input into a table on Excel 2016. The mean, standard deviation and standard deviation of the mean were calculated for the values obtained from BitePrint© software.

Data was inputed into excel to run ANOVA test; ANOVA: two-factor without replication. From
there, the intraclass correlation (ICC) and approximate confidence interval with a 95% confidence interval for the ICC were calculated.

RESULTS

Comparison of Digital Calliper and BitePrint© Software values

The width of the front four tooth (incisors) of each dental cast was measured by a digital calliper, and the Biteprint© software which automatically computes the parameters of the tooth mark from the impression on the dental wax sheets after standardising the software.

Table 1. The width of the front four tooth of dental cast #1 (top), 2 (bottom), 3 (bottom), 7 (top), and 9 (bottom) measured by a digital calliper.

<table>
<thead>
<tr>
<th>Dental Model</th>
<th>Tooth No.</th>
<th>Digital Caliper - Width of the tooth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Top)</td>
<td>1</td>
<td>8.06</td>
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<td></td>
<td>2</td>
<td>7.97</td>
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<td>3</td>
<td>5.65</td>
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<td>6.14</td>
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<td>2 (Bottom)</td>
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<td>4.60</td>
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<td></td>
<td>2</td>
<td>3.53</td>
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<td>2</td>
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<td></td>
<td>3</td>
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<tr>
<td>7 (Top)</td>
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</table>
**BitePrint© Software: Average Width of the Teeth, Standard Deviation, Standard Deviation of the Mean**

The mean, standard deviation, and standard deviation of the mean were calculated from the measurements obtained from the BitePrint© software for the triplicate results.

**Table 2.** The mean, standard deviation and standard deviation of the mean were calculated from the values computed from the BitePrint© software.

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<th>SD of the mean</th>
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<td>9 (Bottom)</td>
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<td>0.03</td>
<td>0.02</td>
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<td>4.32</td>
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<td>4</td>
<td>4.27</td>
<td></td>
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</tr>
</tbody>
</table>

The calculated average width was used to compare against the measurements obtained by using a digital calliper. The standard deviation was calculated for each dental model from the values obtained from the BitePrint© software to demonstrate how measurements are spread out from the mean.
The differences between the measurements taken with the digital calliper and the mean calculated from the values from BitePrint© software were calculated and input into excel to find the percentage differences.

Table 3. The differences between the mean calculated and the measurements from the digital calliper were calculated

<table>
<thead>
<tr>
<th>Dental cast</th>
<th>Tooth no</th>
<th>Differences</th>
<th>%</th>
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<td>1</td>
<td>0.29</td>
<td>29</td>
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<tr>
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<td>0.89</td>
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<td>2.29</td>
<td>229</td>
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<tr>
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<td>1</td>
<td>0.91</td>
<td>91</td>
</tr>
<tr>
<td></td>
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<td>0.59</td>
<td>59</td>
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<tr>
<td></td>
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<td>0.56</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.62</td>
<td>162</td>
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<td>0.84</td>
<td>84</td>
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<td>-3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.15</td>
<td>-15</td>
</tr>
</tbody>
</table>

**ICC and Approximate Confidence Interval for the ICC**

By using the equations, stated above in the materials and method. The intraclass correlation (ICC) and approximate bound of the confidence interval for the ICC were calculated for each dental model.

Table 4: Anova: Two – factor without replication was done on the set of data from BitePrint©
software for all dental cast. The ICC and lower and upper bounds of the confidence interval for ICC was calculated from the values obtained from ANOVA.

<table>
<thead>
<tr>
<th>Dental Cast</th>
<th>Rows</th>
<th>Columns</th>
<th>Rows</th>
<th>Columns</th>
<th>F</th>
<th>P-value</th>
<th>F crit</th>
<th>Intraclass correlation</th>
<th>Lower</th>
<th>Upper</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>1.07</td>
<td>0</td>
<td>0.4</td>
<td>4.76</td>
<td>5.14</td>
<td>0.81</td>
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<td>0.99</td>
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</tr>
<tr>
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<td>0.08</td>
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<td>0.75</td>
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<td>3</td>
<td>3.51</td>
<td>0.97</td>
<td>0.09</td>
<td>0.43</td>
<td>4.76</td>
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<td>0.46</td>
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<td>0.94</td>
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</tr>
<tr>
<td>7</td>
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<td>0.01</td>
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<td>5.14</td>
<td>0.71</td>
<td>0.06</td>
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<tr>
<td>9</td>
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<td>0.01</td>
<td>0.05</td>
<td>0.99</td>
<td>4.76</td>
<td>5.14</td>
<td>0.62</td>
<td>-0.15</td>
<td>0.97</td>
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</tr>
</tbody>
</table>

**DISCUSSION**

Dental casts and their impressions on wax sheets were used to investigate the reproducible and accuracy of the BitePrint© software. The upper, lower, lower, upper, and lower maxilla were chosen for dental model 1, 2, 3, 7, and 9 respectively for this experiment. The maxilla chosen were mostly straight, spaced apart, and levelled except for dental model 2 where the teeth are crooked.

Dental wax sheets were used as a replacement for human skin because it had the advantage
of not distorting, and the teeth position were known. Whereas, there are many factors to take into considerations if the human skin was used. Dental wax sheets type 4 was commonly used by technicians to create the preliminary denture base. It has good handling properties and makes tooth setting easier and faster. Furthermore, it is low warpage and shrinkage\textsuperscript{12}.

**Measurements from BitePrint\textsuperscript{©} Software**

A triplicate impression of each dental cast was used to test the repeatability of the software. From the values in Table 2, the average and standard deviation (SD) for each tooth of each dental model was calculated as shown in Table 2. Standard deviation is calculated as it informs how spread out the measurements is from the average value. A low standard deviation will indicate that most of the measurements are very close to the average whereas a high standard deviation indicates otherwise\textsuperscript{13}. The standard deviation of the mean is the standard deviation of the sampling distribution. Therefore, the standard deviation of the mean will be affected if the effect of random changes is significant\textsuperscript{14}.

The standard deviation and the standard deviation of the mean are used for testing repeatability. Therefore, the smaller the value is, the higher the repeatability, and therefore the reliability of the results will be higher. It will be ideal for the value to be 0 as it means that there are no differences among the results. As seen in Table 2, none of the value for standard deviation or standard deviation of the mean was 0. This could be due to the software being semi-automatic. It requires operator input for the axis of the tooth mark and depending on the pressure applied to the dental wax sheet with the dental cast; the same tooth could create a mark that looks slightly different. Hence, creating a variance on the axis drawn on the software. The force of the pressure applied could be part of the controlled variables for future
studies.

From Table 3, it could be seen that 10 out of 20 measurements were over 50%. This could imply that the software is not able to produce similar value as the digital calliper. The digital calliper provides a more accurate value as it is able to measure the width of the tooth from end to end unlike the BitePrint© software. In the software, the operator is unable to input the axis exactly from the end to end as the line that could be drawn for the axis are not flexible. Therefore, the axis that are input by the operator are smaller than original axis.

**Intraclass Correlation (ICC) and Confidence Level for ICC**

From Table 4, Intraclass correlation measures the reliability of measurements for clusters. A high ICC value suggests a high similarity between the values from the same groups, whereas a low ICC value says otherwise. It will be ideal for the ICC value to be close to 1. The approximate lower and upper bounds of the confidence level for the ICC informs that the mean is between the lower and upper bound of the confidence interval. Also, it provides an estimation of the uncertainty of the mean. It could be seen that the ICC for 3 out of the 5 dental cast chosen were below 0.75 indicating that the reproducibility is not excellent as opposed to the study by Ramos et al. This might be due to this experiment taking only one measurement from the software unlike the study by Ramos et al where dental parameters such as distance to the arch, angular position, eccentricity, rotation, and intercanine distance were taken into consideration. These dental parameters could be taken for reproducibility testing in future experiments. Furthermore, it was mentioned in the study by Ramos et al that the distortion and errors that are created by 2D technology would have a negative effect on the digital measurement process.
In a study by Bell\textsuperscript{16}, it was shown that the ABFO No. 2 scale is not absolutely accurate as the circular references on it are not all the same nor actually circular. There are differences between the circles on and between scales. This could be overcome by using the same scale throughout the study.

**CONCLUSION**

The low standard deviation and standard deviation of the mean shows that the software is able to produce reliable results. However, the differences between the actual value and the average measurements from BitePrint\textsuperscript{©} software shows that the values from the software are not accurate. Furthermore, due to time constraint and limited materials, the reproducibility testing could be improved. Although the current study has provided an insight on how reliable the software is, there is a need for further research to validate BitePrint\textsuperscript{©} software.

**ACKNOWLEDGEMENTS**

The author would like to thank Dr Stephen Knott for his valuable advice in the construction of this experiment. In addition, the author would like to extend thanks to the co-authors for the valuable comments and help. Finally, to the friends and family who had provided help in one way or another, the author would like to extend great gratitude.

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