Forensic Investigation of Static Bare footprints Sampled from Three Distinct Races; White British, Chinese And Indians.

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Abstract

Bare footprints, marks or impressions found at crime scenes can potentially provide criminal investigators with intelligence relating to the stature, gait of a perpetrator or aid the reconstruction of a crime scene. Currently, little is known about the inter- and intra-variations in bare footprint morphologies or the prevalence of certain characteristics in bare footprints from distinct races. To understand such variability requires large datasets of bare footprints. One of the primary aims of this thesis was to develop a novel, inexpensive method to record control samples and use the method to generate large datasets of bare footprints. The reliability of this method was investigated, and the qualitative and quantitative results indicated that there was repeatability and comparability between the new method (lotion) and the industry standard existing methods, for example, the inkless shoeprint kit and fingerprint ink. Following the successful testing of the lotion method, the lotion was used to gather static control bare footprints from three distinct races, White British (n = 25); Chinese (n =25); and Indian (n = 25). The quantitative data consisting of the footprint dimensions were converted to ratios. In addition, the foot outline was converted to morphological landmarks and the data was analysed using principle component analysis (PCA) and model-based cluster analysis (MBCA) to investigate the relationships between the three races. The results showed that the data from the three races could be placed into their respective racial groups using the *x* and *y* morphometric landmark coordinates. The resulting bare footprints data generated during this project was subsequently used to establish a database in Microsoft Access Database (MAD) to allow the data to be stored and new data to be added in, for future research work.

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CHAPTER 1: Introduction

1.1 Introduction

Before exploring bare footprint analysis, it is important to note the context in which the terms "footprints", "the foot", and "bare footprints" are referred to in the literature. Different authors will refer to different meanings and it is important to be aware of the context and meaning of each term. For example, the term footprint is used by other authors to denote shoeprints (two-dimensional or three-dimensional) (Bodziak 2000). Other publications use the term "foot" refer to the whole foot (e.g. all anatomical regions of the foot, including the skin) (Sen and Ghosh 2008). However, the term bare footprints is common in forensic podiatry as this is used to denote patent prints produced when the friction ridge skin on the undersole (contaminated with a coloured substance e.g. ink or paint) is captured and retained by a high contrast background (Burrow 2016; Reel et al. 2010).

1.2 Forensic analysis of bare footprints

In the context of forensic science, pedal evidence which includes bare footprints, marks or impressions are mainly examined to determine if a perpetrator has been present at a place of interest or crime scene (definitions of bare footprints, marks and impressions are discussed more in section 1.3). Forensic analysis of bare footprints, marks or impressions can potentially help determine if unknown barefoot evidence found at the crime scene and controls or exemplar prints sampled from a suspect were produced by the same foot (Kennedy et al. 2005a; Reel et al. 2012; Dimaggio and Vernon 2017; Krishan 2007). Chapter 3 further discusses bare footprints controls or exemplars collected from the suspect on request by the police. Bare footprints are often found at homicide or crime scenes where sexual assault has occurred, such as domestic settings where serious injury or death would have occurred (DiMaggio and Vernon 2017; Kennedy et al. 2007). Barefoot evidence found and recovered from crime scenes have played pivotal roles in the conviction of criminal perpetrators (Vernon 2006; Kanchan et al. 2012; Reel et al. 2010; Kennedy and Yamashita 2007; Kennedy 2005). It is indicated by Kennedy et al (2007) and Hammer et al. (2012) that the intelligence acquired from analysing barefoot evidence can potentially assist investigators to make decisions of whether to include or exclude a suspected individual from an investigation, for example, Crown vs. Clarke 2005. According to DiMaggio and Vernon (2011), Clark murdered his parents and he managed to dispose the incriminating blood stained clothes and weapon. But, during the commission of the crime, he unwittingly left behind latent footprints which were later identified as belonging to

him. Barefoot evidence can also facilitate the reconstruction of a crime scene, for example, the positioning (orientation) or their location (bare footprints, marks or impressions) in relation to objects of interest such as a weapon, door, blood spatter or deceased victim, can aid investigators understand the chronological order of events leading to the tragic result (DiMaggio and Vernon. 2017). In addition, bare footprints, marks or impressions found at a crime scene can potentially inform forensic podiatrists about the gait of a suspect. For example, this is achieved by collecting and analysing a series of bare footprints produced by the same person during their normal gait (Burrow 2015a). As the science of barefoot evidence analysis is being realised, such evidence is gradually becoming prevalent in court proceedings and criminal investigations (Nirenberg 2016; DiMaggio 2005; Dimaggio and Vernon 2017).

1.3 Bare footprints, marks and impressions.

When barefoot evidence is initially encountered at crime scenes, they are either two-dimensional or three-dimensional (Burrow 2015; DiMaggio and Vernon 2011; 2017). Two-dimensional marks or prints are formed when the foot weight bearing area encounters compact surfaces, for example, ceramic tiles, vinyl mat, wooden tiles or concrete. Whereas, three-dimensional impressions are formed when contact occurs between the foot weight bearing area and malleable surfaces, these include, carpets, thick fabrics and for outdoors moist soil or snow (Jira 2017; Curran and Holmes 2019). In addition, two dimensional footprints and marks can be subcategorised in two forms. These are latent marks, and patent prints. Latent marks are usually invisible to the eye and might require special lighting to locate them (Burrow 2015; DiMaggio and Vernon 2017). The adoption of fingerprint development techniques would be required to enhance the marks to allow photographic capture. For example, crime scene lights (White 400-700nm, Blue 420-470nm, Blue/Green 450-510nm, Green 490-560nm or Red 600-650nm) can be introduced to optimize and photograph the latent marks (Jira 2017). However, bare footprints are formed when the foot weight bearing area, particularly the friction ridge skin comes into contact and becomes contaminated with a coloured substance like blood, paint or inks (Jira 2017). According to Curran and Holmes (2019), bare footprints are sometimes found at crime scenes in the form of static or dynamic forms, for example, dynamic bare footprints are produced during the dynamic phase of gait (walking); and the static bare footprints are produced whilst in a static erect posture (standing). According to (Reel 2012) and Burrow (2015), bare footprints can be identified as being static or dynamic by the presence of ghosting if they were produced during dynamic or static phases (Reel 2012; Burrow 2015).

According to Burrow (2015a) and Reel (2012), bare footprint ghosting is referred to as the lighter shading on the footprints which extends beyond the normal weight bearing area of the barefoot. Even though ghosting is reported to be more likely in dynamic bare footprints, it is also reported by Burrow (2015a) and Reel (2012), found unusual ghosting in static bare footprints produced by two participants. More generally, static bare footprints can be seen as standardised samples depicting the actual weight bearing area of a foot (Mathieson et al. 1999)

Predominately, present studies in bare footprints analysis have focussed on the uniqueness of individual bare footprints (Kennedy and Yamashita 2007; Kennedy 2005; Gunn 1991; Rossi 1992; Kennedy 1989; Kennedy and Pressman 2003). The outcome of these investigations have helped shape and develop footprints analysis to become appreciated by professional bodies in forensic science. For example, a recent study conducted in the UK investigated two dimensional static bare footprints and fleshed foot dimensions from a white British population (Curran et al. 2019). This study identified that actual foot size could be estimated using a regression equation of 19.89 + 0.95 x print length ± 8mm. This is an improvement from the previously studies by Dimaggio and Vernon (2017) who suggested adding a fixed amount of 1.5 or 2.0 cm to the length of the footprint. This study also identified that sex was not a significant predictor in the their used in their study. This information is vital and can be used by investigators narrow down their search of the perpetrator to a more focused search. These studies particularly benefit investigators when they are trying to estimate whether a particular foot size, shoe insole and bare footprint are all linked to the same perpetrator. Additionally, other studies conducted by Krishan et al. (2011); Reel et al. (2012); Krishan et al. (2015); Krauss et al. (2010); Krauss et al. (2011) and Abledu et al. (2015), have also provided invaluable knowledge of what biological information can be gained from analysing bare footprints and marks. For example, these studies have highlighted how the bare footprint can provide an estimation of stature and sexual dimorphism. According to Fessler et al. (2005) and Krishan et al. (2015), human bare footprints can be used to distinguish the sex of the donor, for example, friction ridge density and the average dimensions of female and male feet (Krauss et al. 2000; Krauss et al. 2011). Consequently, there is no new information or any new significant discoveries concerning variations in bare footprint morphologies, since the studies conducted by Kennedy and Pressman (2003) and Kennedy et al. (2005) which investigated the uniqueness of bare footprints for the purpose of individual identification, from a heterogeneous sample (Please see further discussions in Chapter 6, section 6.1 and chapter 7, section 7.2). The

findings of the Kennedy papers provided insight into the uniqueness of individual bare footprints and the odds of finding a match in the general population of bare footprints obtained from different individuals.

1.4 Current methods of evaluating bare footprints

Current literature on bare footprints analysis, suggests that there are seven methods used to evaluate bare footprints. The seven methods can be classed in to two groups. For example, group one consists of methods for individual characterisation for the purpose of identification; and group two consists of methods for classifying foot typologies (for identifying suitable footwear) or diagnosing foot pathologies (Murkhra et al. 2018). Table 1.1 illustrates the two groups, the parameters that are measured and the application of the method.

Bare Footprints Evaluation Method	Parameter Type	Application
Gunn method including the extended Gunn method	Linear measurements	Identification purpose
Robbins diagonal and parallel method	Linear measurements	Identification purpose
Reel method	Linear and angular measurements	Identification purpose
Rossi's podometrics method	Linear measurements	Foot type
Optical centre method	Linear measurements	Identification purpose
Overlay method	Morphology	Foot type and identification purpose
Geometric morphometric method	Morphology	Foot type

Table 1. 1: Illustration of bare footprints evaluation methods, type of parameter measure and the application

Murkhra et al. (2018) also acknowledges that, bare footprints are not always found in a state that is easy to interpret. The manner in which the bare footprints were deposited or the substrates in which they were produced may make it difficult to interpret. Individual characteristics contained within a bare footprint, mark or impression can potentially be destroyed if trodden upon. Therefore, methods such as the extended Gunn method (Figure 1.2) or angular method (Figure 1.4) devised by Reel (2012) can potentially be used to evaluate partial prints or marks (if no friction ridge detail is available for the dermatoglyphic examiner

to evaluate). To date, some of these methods are still being used to evaluate two-dimensional bare footprints and three-dimensional barefoot impressions. In a forensic context, evaluating bare footprints using linear measurements consists of measuring the length and width of the footprint. For example, distance from the posterior of the heel to the furthest point of each exhibited toe and the width of the widest point of the (i) heel ball and (ii) width of the ball (Reel et al. 2010). Other evaluation methods do not require measurements but instead focus on the morphology of the footprint outline (weight bearing area) (Figure 1.9). Currently, the Reel measurement method has been suggested as the most reliable and recommended for evaluating two-dimensional static and dynamic bare footprints recovered from crime scenes (Reel et al. 2012; Reel et al. 2010). The Reel method demonstrated a high intra-rater reliability and intra-class correlations of 0.98 to 0.99, with a 95% standard error measurement in a controlled environment (Reel et al 2010; Nirenberg et al. 2019). This method has since been adopted by the forensic podiatry community as the most reliable and best practice for forensic casework (Dimaggio and Vernon 2017; Burrow 2015; Nirenberg et al. 2019). However, other evaluation methods might also be employed depending on the quality of the footprint(s) or the circumstances in which they were produced. In the case of Crown vs. Clarke, two methods were used in combination to conduct comparisons of the prints found at the crime scene where the parents of the suspect had been murdered. The suspect had managed to destroy evidence but was convicted of the murder after both the Gunn method and the overlay method had suggested the known and unknown footprints originated from the same source (suspect) (Dimaggio and Vernon 2017). According to DiMaggio and Vernon (2011; 2017), the overlay method, Rossi's method, the Gunn method, the optical centre method, Robbins method, the Reel method have all been used in criminal case work. These approaches to evaluating two and three dimensional bare footprints have until present aided forensic investigators determine whether a certain individual of interest is associated with a questioned sample recovered from the crime scene. However, there are other methods that are used to identify foot types (Table 1.1) and there has been an attempt by some researchers to investigate if these methods can be used for individual identification purposes, based on the shape of the weight bearing area. For example, the geometric morphometric method suggested by Domjanic et al. (2013). The methods presented in Table 1.1 have either been used in criminal casework or anthropological research (Rossi 1992; Gunn 1991; Reel 2012; Yamashita 2010; Laskowski and Kyle (1988); Krauss et al. 2011; Krauss et al. 2000; Stavlas et al. (2005). A brief summary of the methods are presented below from section 1.4.1 to 1.4.7. Consequently, not all the methods mentioned above are applicable for individual human identification, but for those that are not applicable

to forensic science are often used by clinical podiatrists to diagnose foot pathologies. Below is a brief outline of the methods currently used to examine bare footprints (further discussions of the methods which are relevant to this thesis are discussed in Chapter 6)

1.4.1 The Gunn Method

The Gunn was devised by a forensic podiatrist from Canada, Dr. Norman Gunn (DiMaggio and Vernon 2011). According to Gunn (1991), the Gunn method consists of constructing five lines diverging from the rearmost point of the heal to the distal tip of the phalanges of the phalanges of each toe and a sixth line constructed on the widest part of the foot, from the medial side of the ball to the lateral side of the foot. Once all the lines have been constructed, they are measured individually and a comparison can be made between known bare footprints and unknown footprint. Mukhra et al. (2018) indicates that the Gunn method is applicable if the footprint is captured in its entire form. However, if a partial bare footprint (with missing heel) is recovered, then the extension illustrated in Figure 1.2 can be applied. The linear measurements from the extended version can be measured in the same way. In addition, this method also allows for angles to be measured from each line, providing additional quantitative data for comparative evaluation (Gunn 1991).

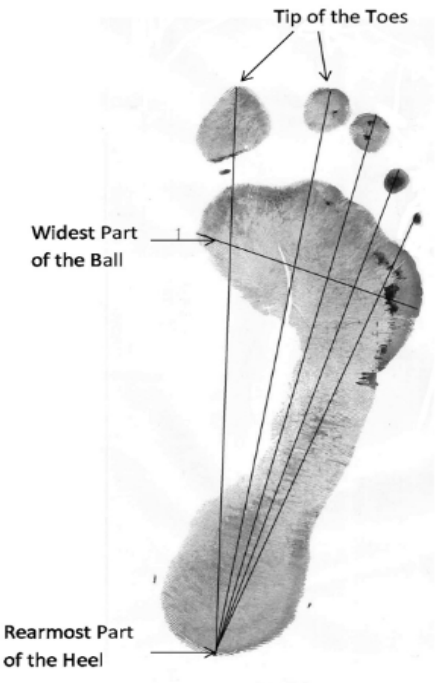

Figure 1. 1: Illustration of the Gunn method of measurement (Mukhra et al. 2018)

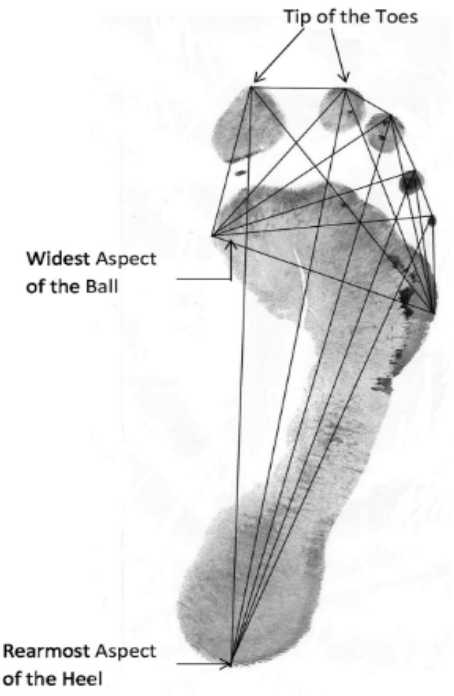

Figure 1. 2: Illustrating the extension of the Gunn method of measurement (Mukhra et al. 2018)

1.4.2 The Reel Method

The Reel method was devised by a leading forensic podiatrist in the UK, Dr. Sarah Reel (Reel 2012). This method consists of the same lines as the Gunn method but, with an additional line, namely the heel widest point. This method uses a total of seven lines (Reel et al. 2012b). This method has been tested for reliability in assessing two-dimensional bare footprints and has proved to be robust. Currently, this method has been adopted by practitioners and bare footprint researchers as the best practice for evaluating two-dimensional bare footprints for research purposes or criminal casework (Burrow 2015; DiMaggio and Vernon OBE 2011; 2017).

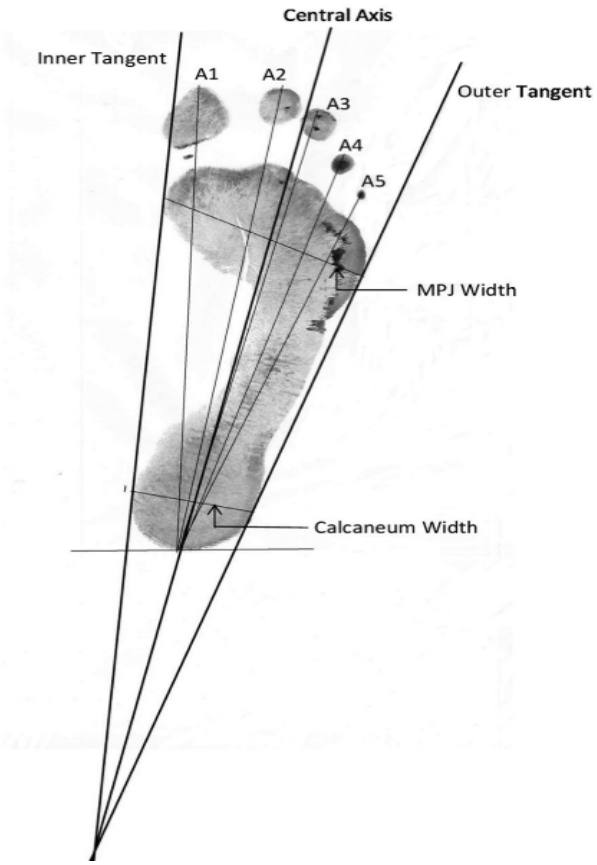

Figure 1. 4: Illustration of the Reel method (Mukhra et al. 2018)

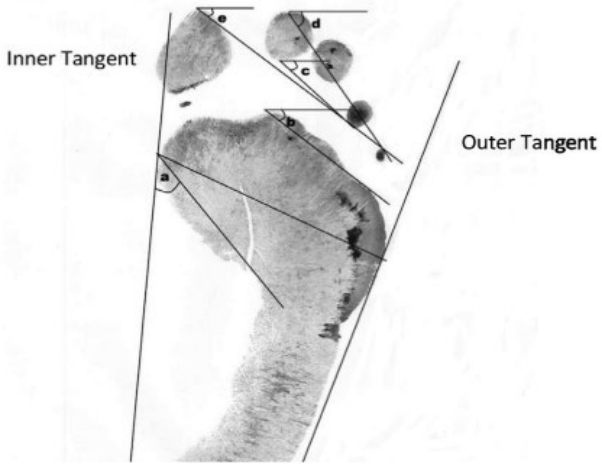

Figure 1. 3: Illustration of the extension of the Reel method, approach to measuring angles (Mukhra et al. 2018)

1.4.3 The Robbins' Method

The Robbins method was devised by an American forensic anthropologist (Robbins 1987). Robbins' method allows for two methods to be used in combination, the diagonal method and the parallel axis method (Figure 1.5 and Figure 1.6). These two approaches utilise visual anthropological measurements, some of which are the same as the Gunn method. The Robbins' method is capable of measuring both two-dimensional and three-dimensional bare footprints, marks or impressions, and allows for the length, width and angles to be measured. According to Mukhra et al. 2018, a transparent metric grid is used to align the footprint vertically with a line in the centre of the footprint known as the designated longitudinal axis (DLA) which provides the footprint with a zero-reference point. This method also allows for right-angled lines to be constructed from a theoretical baseline across the rearmost point of the heel to the furthest point of each toe. An additional line measuring the angle declination is constructed from the first phalanx to the fifth phalanx (Robbin, 1985).

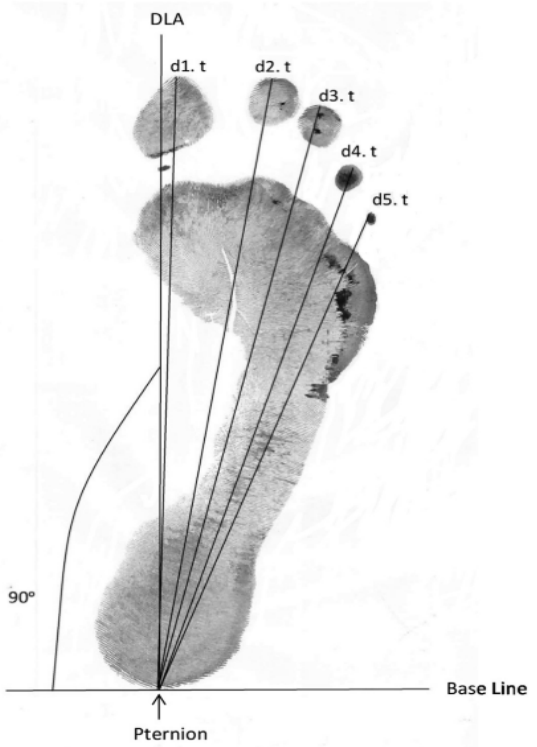

Figure 1. 6: Illustration of Robbins diagonal method (Mukhra et al. 2018)

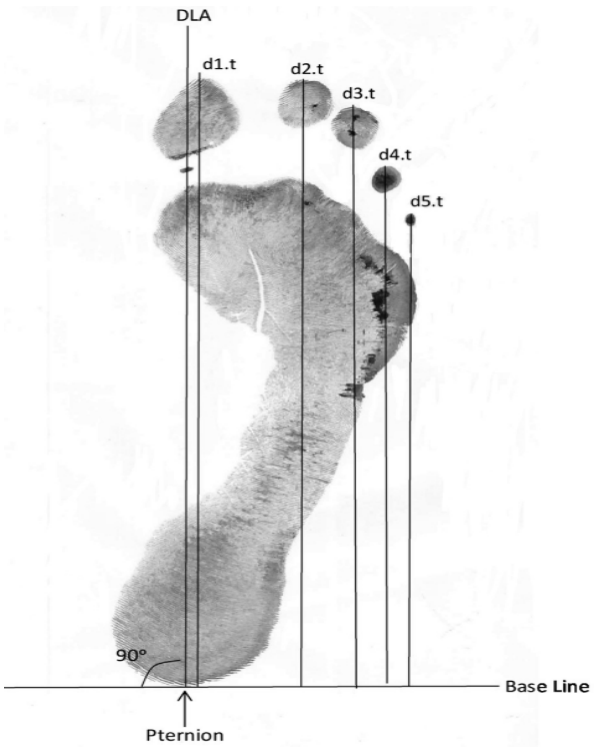

Figure 1. 5: Illustration of Robbins parallel axis method (Mukhra et al. 2018)

1.4.4 Rossi's 'Podometrics' Method

This method was devised by an American podiatrist, William Rossi (1992). This method consists of plotting a grid of longitudinal and transverse lines across the entire surface of the footprint, a system referred to as 'podometrics'. According to Rossi (1992), quantitative data can be obtained from the Rossi method using angle and distances between intersecting points of the longitudinal and transverse intersecting lines. Each intersecting point can be used to map the shape of the foot (Rossi 1992)

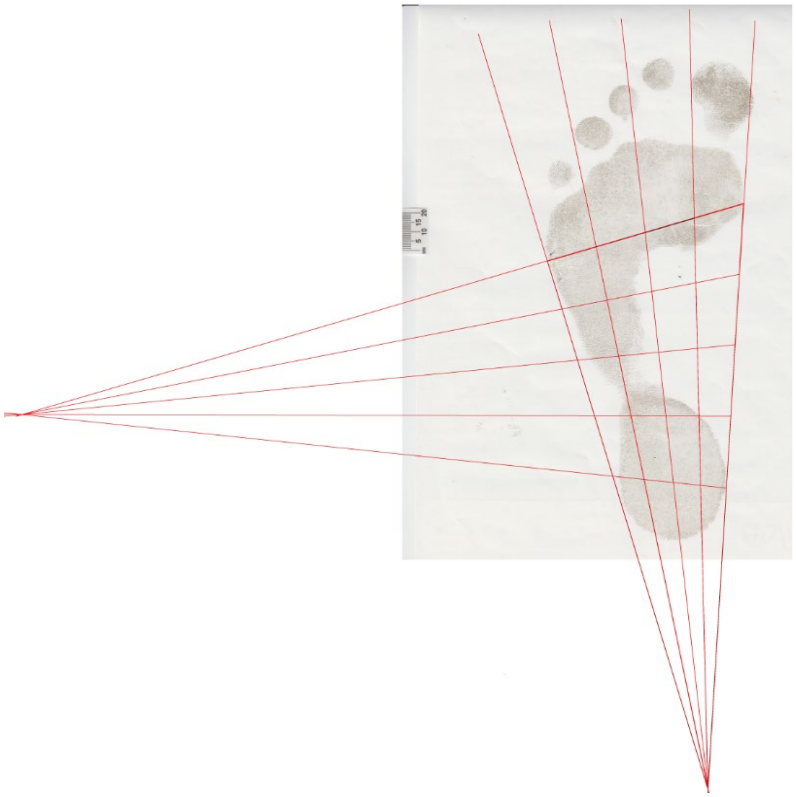

Figure 1. 7: Illustration of the Rossi's method for measuring two-dimensional bare footprints (Rossi 1992).

1.4.5 The Optical Centre Method

The optical centre method was developed by the Royal Canadian Mounted Police in the 1990s (Kennedy et al. 2005; Kennedy and Yamashita 2007). This method assigns an optical centre (most centre point) on any of the morphological features exhibited by the foot in question (e.g. toes or heel). According to Vernon (2007); DiMaggio et al. (2011) and Mukhra et al. (2018), a circle is placed in a position of best fit on each of the toes and the heel (figure 1.5). Using the circle centre point, the Gunn method is then used to construct five lines from the central point of the heel to the central point of each toe and a single line of the width of the ball. The lines are measured and compared to an unknown and exempla footprint.

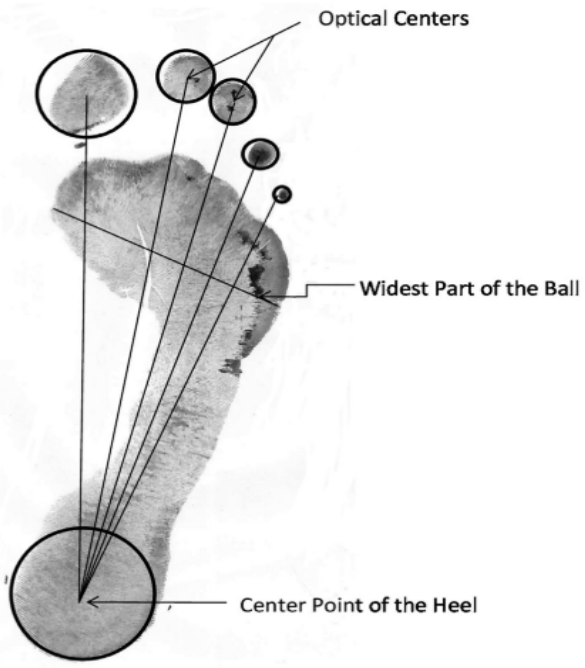

Figure 1. 8: Illustration of the Optical Centre Method (Mukhra et al. 2018)

1.4.6 The Overlay Method

The overlay method was developed in the UK by the Forensic Science Service (Vernon 2007). This method uses a traced outline of a known footprint instead of the linear measurement approach (Vernon 2006). To conduct a comparative analysis between known and unknown footprint, the outline of the known footprint is traced on to a clear acetate card and this is overlaid on to the unknown footprint. This analysis involves comparing the overall positions and characteristics of the two, to assess how best these features fit, and if the morphological outline is clearly represented.

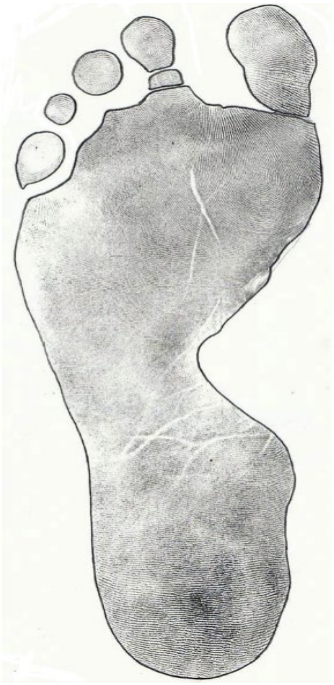

Figure 1. 9: Illustration of the Overlay Method (Mukhra et al. 2018)

1.4.7 The Geometric Morphometric Method

This method was developed in Austria by researchers investigating the morphological variations between bare footprints collected from a sample of 83 women (Domjanic et al. 2013). This method uses a comprehensive set of 85 landmarks and semi-landmarks (Shape coordinates), to map the footprint outline. These shape coordinates are compared using Generalised Procrustes Analysis (Bookstein and Domjanic 2015; Domjanic et al. 2015; Domjanic et al. 2013). This method was initially designed to record the shapes of archaeological artefacts, catalogue shapes, for example fish or insect species (Börstler et al. 2014; Webster and Sheets 2010; Ball et al. 2010). Using a comprehensive set of landmarks, the user is able to plot landmarks on curved sections (Figure 1.10), making this method suitable for capturing non-linear sections. However, this technique cannot be used to measure the length or width of the foot but, to map the bare footprint outline using x and y morphometric coordinates. This method is further discussed in chapter 6.

Figure 1. 10: Illustration of the Geometric Morphometric Method (Domjanic et al. 2015)

1.5 The Impact of Advances in Technology on Bare footprints Analysis

In the past, evaluating bare footprints for research and criminal casework was usually conducted using straight-edge metric rulers and pencils (depending on the substrate) (Rossi 1992; Kennedy 2005; Reel 2012). This manual approach still remains effective and is occasionally used as an alternative method to capture footprints dimensions. But, the improvements in technology has seen a gradual increase in the number of researchers and forensic podiatrists moving to adopt computer measuring programs. According to Nirenberg et al., (2019), computer measuring programs have a lower margin of error when compared to manual methods that have been the norm since the evaluation of two and three dimensional bare footprints began. The emergence and adoption of approaches in forensic podiatry saw a need to validate these methods for forensic use, to ensure that they meet the *Daubert* standards for court admissibility. To date, Adobe® Photoshop® and open source software GIMP (GNU Image Manipulator Program) software are reported in forensic podiatry text and are widely recognised as the industry standard (DiMaggio and Vernon, 2011; Reel 2012). According to Nirenberg, GIMP is an open source software that has been validated for use in forensic casework by Reel (2012). Carrier (2018), also highlights that open source programs such as GIMP, advance and debug more rapidly because they are easily accessible and open to peer review. These computer programs have since taken the place of manual recording techniques adopted by well-established forensic podiatrists (Burrow 2015; 2016; Reel 2012; Hammer et al. 2012b); DiMaggio and Vernon 2017). Nirenberg et al. (2019) conducted an investigation of two dimensional dynamic bare footprint and the outcome of the study highlighted that even though there were small mean differences between the seven linear measurements (measured using the Reel method) acquired using three techniques: (i) manual measuring approach; (ii) Adobe® Photoshop® technique; and (iii) GIMP GNU Image Manipulation Program, there was no statistically significant difference between the three techniques. The outcome of this investigation is expected because computerised techniques are more precise than manual methods. In this instance, the operator conducting the measuring has greater control of where on the image they should start measuring from, as well as the advantage of having close-up or 'zooming' application tools which are not available with the manual measuring approach. Thus, there is greater technical control over the measurement tools as opposed to manual methods. According to Reel (2012), once the operator sets the pencil thickness they require for measuring, this setting remains consistent throughout the entire measuring process. On the other hand for the manual method, as the pencil is used and wears out and the line gradually thickens, potentially influencing where the quantitative measurement is recorded from. This

makes the digital methods superior, hence the recommendation from the forensic podiatry community to use these methods. Furthermore, not only are these types of software used in footprints analysis, but they are also employed in other forensic science programs, for example, forensic examination of marks (e.g bite marks or tool marks) (Osborne et al. 2014; Hannigan 2002; Levin 2013). The findings of the use of these softwares are published in some of the most influential peers reviewed periodicals. However, it should be noted that 'forensic podiatry' is still in the developing stages and the first book dedicated to this discipline was first published in 2011, with the second edition published in 2017 (DiMaggio and Vernon 2011; 2017).

Biomechanics research, which sometime overlaps with forensic podiatry, has also seen the gradual use of technology such as pressure plates and load sensors to assess each individual's foot weight distribution (Wrbaskić and Dowling 2007; El-Hilaly et al. 2013; Urry and Wearing 2005; Urry and Wearing 2001). The past decade has seen technologies evolve and the adoption of new computerised techniques. The concept of using three-dimensional foot scanners to assess the weight bearing area of the foot has seen researchers attempt to investigate bare footprint morphologies (Domjanic et al. 2013). These studies captured the barefoot outline and used geometric software to record and analyse morphometric landmarks. In addition, three-dimensional foot scanners have also been used in clinical research to assess the foot shapes, thus allowing the design of comfortable shoes (Baek et al. 2012). However, as important as these studies may be, they do not account for the multitude of variables which affect bare footprints found on different floor surfaces. For example, footprints recorded using three-dimensional foot scanners are not comparable to two-dimensional bare footprints or marks produced on different floor substrates. To date, there are researchers who have managed to adopt similar concepts to try and answer the question of morphological variation in footprints from different individuals (Domjanic et al. 2013). The potential of using this computer software has been realised in evolutionary science (Bonhomme et al. 2013). For example, Mome-clic software, MorphoJ software, and the software developed by Jim Rolf at the Stony Brook campus of the State University of New York (http://life.bio.sunysb.edu/morph/), which have enabled biologists to investigate the origins of certain animal and insect species (Börstler et al. 2014; Sheets et al. 2013).

1.6 Evolution of the Human Foot

According to D'Août and Aerts (2008), the human foot anatomy is highly complex, it consists of 26 skeletal elements, intrinsic and extrinsic muscles which are connected by ligaments. The functional studies of the foot have shown that there are multiple interactions, some of which conflict during gait (D'Août and Aerts 2008). In addition, the skeletal elements of the foot, ligaments and tendons all form a flexible structure which reduces strain during gait. The foot also acts as a shock absorber to soften the impact during locomotion and adjust to the substrate, whilst maintaining balance (Susman 1983; Miller-young et al. 2002). The evolutionary history of the foot requires understanding functional requirements of the modern foot and its evolutionary history from the early hominin, chimpanzee to human beings. According to Susman (1983), the human foot has evolved over time to form an elaborate plantar aponeurosis, plantar ligaments, longitudinal arches, an enlarged musculus flexor accessories, an adducted hallux, a remodelled calcaneocuboid joint, a long tarsus, and shortened toes (2 to 5). Examination of fossil foot bones of homo habilis dated 1.76 million years show similarity to the human foot (Susman 1983). It is also indicated by Susman (1983) that the foot bones found in Ethiopia, dated to 3.5 million years are similar to the chimpanzee, with incipient characteristics of the human foot. These fossils strongly support how the human foot evolved to what it is today.

According to Morton (1940), there are three principal changes required to transform the ape-like foot into a terrestrial human foot. First, the changes require transfer of locomotor functions from the arms and hands to the legs and feet, secondly, increase in the intrinsic base of support of the foot structure (bones, ligaments and tendons) by lowering the heel to the ground, and thirdly, cessation of the grasping ability and the foot becomes a lever for lifting and propelling the body forwards. This is significant when considering humans have evolved from ape-like ancestor to modern human with bipedal locomotion (Harcourt-Smith and Aiello 2004). However, the friction ridge skin also plays an enormous role in ensuring grip is maintained. According to Fieldhouse (2009); Werthein and Maceo 2002), the structure of friction ridge skin is made up of two layers, the outer epidermis, and the inner dermis (Figure 1.9).

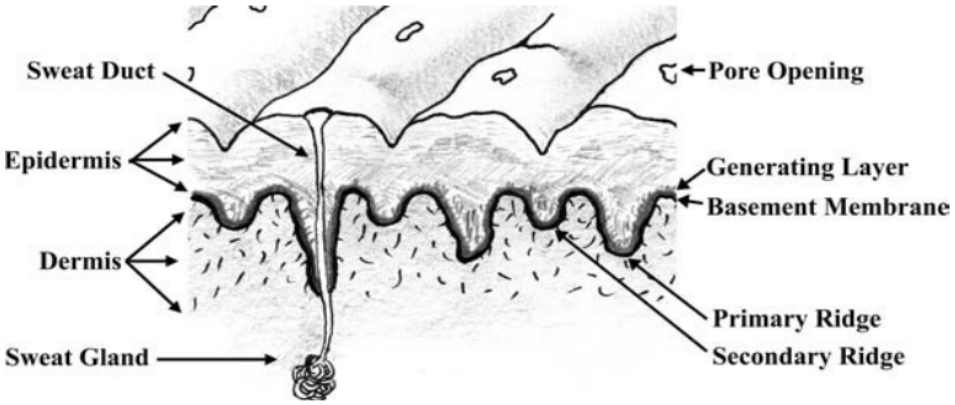

Figure 1. 11: Illustration of a three-dimensional cross section of the structure of mature volar skin (Werthein and Maceo 2002).

These two layers are separated by a membrane which acts as a boundary and a mechanical linkage between the two layers. Werthein and Maceo (2002), further indicates that the epidemis is devided into five cellular layes which are based on intrinsic changes in the cells as they progress from the bottom of the epidemis to the surface of the skin. The dermis is devide into two layes, reflecting differences in fibre composition. The foot undersole is comprised of surface ridges and furrows which are arranged in a series alongside each other. The comparisons between the chimpanzee and human volar skin has shown how the foot undersole friction ridge skin has evolved to form a layer that is resistant to slipage (Werthein and Maceo 2002).

1.7 Foot morphology, culture and lifestyle

To begin to understand how fragile the foot structure is, it is important to explore literature that has focused on foot morphology differences or foot binding that was once practiced in ancient China. According to Shu et al. (2015), there is evidence which supports foot morphological differences influenced by lifestyle. For example, habitually shod individuals tend to have a narrower foot structure when compared to habitually unshod individuals (Shu et al. 2015). Lifestyle choices of footwear and gradual use of certain types of footwear, for example, high heel shoes is associated with a lager forefoot area of the footprint and a hallux that exceeded the length of the other toes (Domjanic et al. 2015). Women who wore high-heeled shoes more often tended to have hallux valgus a form of forefoot deformity (GU et al. 2014; Domjanic et al. 2015). However, there are cruel methods referred to as “footbinding” which were practiced in China during the 10th to and 20th centuries. The foot morphology was deliberately altered by binding the foot to create a small three inch foot (Strochlic 2014). This process was done to a

girl child at the age of six to eight, at an early stage when she couldn't resist or say no (Bossen et al. 2011). To begin the binding process, the child's feet were bound using bandages to force the foot morphology to permanently change (Mackie 1996; Strochlic 2014). Mackie (1996), indicates that the binding would continue every day for a period of nearly ten years until the foot morphology had reduced in size. See figure 1.10, an image showing a foot that has undergone foot binding (Szczepanski 2018).

Figure 1. 12: Illustration of the foot which has undergone foot binding (Szczepanski 2018)

The foot binding process involved crushing and breaking the 26 bones of the foot to archive a three-inch lotus feet (Bossen et al. 2011). Pressure was applied by wrapping bandages tight each time and this would cause overtime the arch to break (Cummings et al. 1997). This process would not guarantee that all the toes would be intact after the process. According to Stone (2012), foot binding did not always produce the intended results, sometimes the results would be disastrous and the process could not be reversed. For example, they were some complications which include, paralysis, gangrene, ulcerations and mortification of the lower limbs. Nearly 10% of the girls did not survive from the effects of foot binding (Mackie 1996).

Please see Figure 1.11 which shows the foot bone structure before binding, during binding and after binding process.

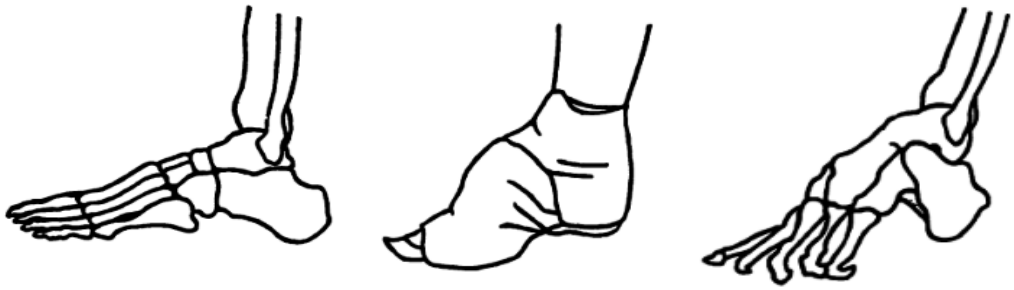

Figure 1. 13: Illustration of the foot binding process, before, during and after (Cummings et al. 1997)

Altering the foot morphology to acquire a desired shape was once seen as a sign of wealth and marriage eligibility (Bossen et al. 2011). A mother would subject her child to this cruel process because they believed it was the best for their daughters. According to Brown et al. (2012), the consequences for not binding the feet meant that the prospects of marriage were very low. There were high chances that the child would end up as prostitute, rented or sold as a bond servant if their feet were not bound at an earlier stage. It was believed that foot binding by Chinese women demonstrated their artifice, pride and beauty and it was not be seen as oppression of women but, as women being superior and beautiful (Brown et al. 2012). This meant that girls would start at a young age to learn sedentary handwork (Zito 2007). Consequently, bound feet meant little mobility for the girl-child due to the pain. The process was also life changing in the sense that the affected child would not be able play and run around with children of her age (Zito 2007). Despite all this, mothers would oversee the binding of their own child, motivated by the fact that the smaller the feet, the better her marriage prospect (McGeoch 2007). Prospective mothers-in-law would note the bound feet and saw a girl with bound feet as being suitable for their son (Strochlic 2014; Bossen et al. 2011; Brown et al. 2012). In addition, the prospective mother-in-law's, viewed the bound feet as suffering the pain without complaining, they also believed that the daughter in-law would be an obedient wife to their child, as they had already suffered pain.

1.8 Searching the Literature

The literature research was conducted by manually searching the library catalogues and also using electronic library resources. Currently there are two published texts that are dedicated to forensic podiatry, with the first having published in 2011 (DiMaggio and Vernon, 2011). It is evident from the available literature that this discipline is still in the developing stages and there is still much new knowledge to be gained from investigating two and three dimensional bare footprints. For example, the 'population' question remains unexplored in the context of forensic bare footprints analysis (DiMaggio and Vernon et al 2011). It is also evident from the literature that researchers in forensic bare footprints put more emphasis on individual characteristics (as these aid positive identification of the individual), and this supports the evidential aspect more than the intelligence aspect. For example, estimation of race or ethnicity has never been explored fully in the context of forensic science. Conducting this research required the researcher to bring together and combine more than one discipline to develop the research question. For example, 'if there are foot shape differences (reference from normative data measured from certain populations for designing footwear), then surely bare footprint morphologies can be associated to their respective races'. Thus, to begin the literature research, the researcher identified the appropriate key words which could be used for searching online databases. This strategy identified that there were some inconsistencies in the terms adopted by different authors to describe the same thing. For example, there terms footprints, unshod foot, barefoot prints, and foot impressions, were among some of the terms that were used. Therefore, creating keyword alerts containing some of these terms resulted in the accumulation of non-relevant literature. For example, foot analysis and footprints analysis are two distinct areas but one cannot discuss one without the other. The researcher also identified that foot analysis was usually conducted for clinical reasons, such as assessment of foot deformities such as hallux valgus, examination of victim of thalidomide. In addition, foot analysis also includes the examination of the fleshed foot, usually conducted to gather data for designing appropriate footwear for certain populations (Hawes et al 1994). The podiatry discipline touches on four areas which are: clinical podiatry, bare footprints analysis, gait analysis (biomechanics), and footwear examination. Therefore it was vital to be aware of these areas and to be specific in the literature search strategy. So, the literature was categorised into three different groups that were as follows; anthropological literature; clinical and biomechanics literature; and forensic bare footprints literature. It was also identified during the research that there were two areas being suggested by the literature, but one area was covered more than the other, the evidential side had more publications that the intelligence aspect. The majority of the literature covered

the evidential aspect and on the intelligence side, the literature was very limited to sexual dimorphism, and estimation of height and weight. Journal alerts were set up using Google Scholar Alerts, ResearchGate Publication Alerts, BioMed Central Alerts, Mendeley Alerts, Elsevier Journals Alerts, Science and Justice Alerts. This meant that each time an article with specific key words became available on the platform, a notification was sent to the registered emails, allowing the researcher to manually select specific journals. In addition, online journal articles published in Science Direct, Journals Of Forensic Science, Science and Justice, Forensic Science International, International Association of Identification Journal, Egyptian Journal Of Forensic Anthropology, PLOS ONE, Journal Of Foot and Ankle Research, Journal of Forensic Identification, Journal of Punjab Academy of Forensic Medicine and Toxicology, and The Foot were all searched on a weekly basis to identify relevant literature. Mendeley reference management software was used to create a database of journals to allow the research articles to be archived once processed. This process was time consuming because the primary research was focussed on the intelligence aspect, which was not apparent at first glance in the research literature. In addition, knowledge was constructed from combining anthropology, clinical podiatry, biomechanics and gait analysis, forensic bare footprints, and forensic chemistry literature.

1.9 Rationale of The Thesis

Published research relating to foot shapes are predominantly focused on foot dimensions of the overall fleshed foot (GU et al. 2014; Hawes et al. 1994; Lee and Wang 2014; Shu et al. 2015). According to Hawes et al. (1994), foot dimensions are the measurements of the lengths and widths of a foot which is loaded with the full body weight. Many of these studies were conducted to collate normative data for describing shoe shape dimensions and the proportional measurements for certain populations (Hawes et al. 1994; Tomassoni et al. 2014). Furthermore, there are other studies that have investigated race differences in the forefoot but, many of these studies were conducted to inform the design of comfortable shoes (Hawes et al. 1994; Tomassoni et al. 2014; Lee et al. 2014). Even though these studies provide useful information about shoe designs, the question of whether there are morphological variations in 'bare footprints' the data of which can be attributed to race or origin in the context of forensic science, remains limited. However, the studies referred to above, provides important information which supports the notion that, there are racial differences in foot shapes but, these studies are limited to the data gathered only from fleshed feet and not bare footprints (Hawes et al. 1994; Lee et

al 2014; Krauss et al. 2000; Krauss et al. 2011). In addition to this, the quantitative data obtained from the foot methodologies adopted in these studies are not comparable to bare footprints data or the data generated using the recommended methods by the forensic podiatry community (Burrow 2016; Reel 2012; DiMaggio and Vernon 2017). Chapter 6 further discusses the racial differences in foot shapes. It is evident from the available literature that there are gaps in knowledge relating to the inter-and-intra variations in bare footprints morphologies from distinct racial populations, or the extent of the variance if any exists at all. DiMaggio and Vernon (2017) indicates that understanding the morphological variations and prevalence of certain bare footprints characteristics or their combinations in a certain race, for example, Chinese, Indians and the White populations will help forensic podiatrist and bare footprints researchers answer research questions relating to certain casework needs. From a forensic context, understanding if certain racial groups, selected from a pre-defined list of participants can be associated or not, by their bare footprints morphology would have an impact in the area of intelligence. The scientific motivation of this thesis is grounded in two area of forensic bare footprints analysis. These two areas if combined together would benefit forensic podiatry as a discipline and aid the justice system appreciate the value of bare footprints if there are placed before the court as evidence. The first area is evidential value, in the context of forensic science, bare footprints are mostly assessed to determine the probability of a bare footprint, mark or impression found at a crime scene, to belong to a certain individual of interest by evaluating the individual characteristics and the dimensions. The second area is the intelligence aspect, for example, how likely is this individual who deposited a bare footprint at the crime scene would self-identify as belonging to a certain race or population cluster e.g Indian, Chinese or White British. This thesis focuses more on the intelligence element because there is a need to know about probability distributions in bare footprints sampled from individuals who would self-identify as belonging to certain races (and this is powerful in the bigger context of forensic science) this will aid investigation intelligence.

Consequently, using the existing materials to gather bare footprint controls (inkless shoeprint system or fingerprint inks) is either costly or messy. Furthermore, acquiring sufficient data to answer the question of whether there are morphological variations or associations in bare footprints from distinct races is costly, cumbersome and time-consuming. Conducting research of this magnitude requires control sampling materials that are cheap and methods that are standardised, as suggested by the forensic podiatry community (Reel 2012; Burrow 2016; DiMaggio and Vernon 2017). Gathering control samples using methods that are parallel to

available methods will allow for extant data collected using extant methods to be comparable to the data gathered in this study. Thus, the primary aim of this thesis is to develop a cost-effective method using a lotion first developed by Bond (2013a) and investigate if the lotion can be adapted to bare footprint sampling (the lotion is presented in Chapter 2 pilot studies and further discussed in Chapter 4). In addition, this thesis will investigate if lotion can be utilised to generate data that is comparable to the data gathered using the standardised protocol developed by Reel (2012). This overall investigation will also attempt to gather static control footprints from three distinct races (to establish homogenous datasets), thus, to investigate the inter-race variations in bare footprints sampled from distinct races. The results of this thesis will potentially allow forensic podiatrists and academic researchers to answer certain questions relating to race, for example, if bare footprints are attributed to their respective racial population groups.

Before delving into this population study of bare footprints, it is imperative to define race and ethnicity so it is clear what is meant by these terms. It is also important to note that both terms have been used in social science interchangeably to define certain groups of people (Markus 2018). Hence, there is no general agreed definition among social scientists for the precise meaning of these terms, as both terms possess complex meanings that reflect history, culture, socioeconomics, and political status (Markus 2018). It is also important to note that the term 'race' can be viewed as problematic when used to ascribe certain groups of people (Cornell and Hartmann 2007). The connotations associated with the term 'race' has been viewed as racist, or one group having power and privilege over the other groups. However, Lee (2009) defines race as population groups who possess differences and similarities in biological traits that might be deemed to be socially significant by society. These differences or similarities could be colour of the skin (Lee 2009). In biology/anthropology, race indicates genetic variations that can be used to make a reasonably accurate prediction of the geographical origin of an individual and on the other hand, 'ethnicity' is defined as cultural practices that are shared (Cornell and Hartmann 2007). For example, a collective with putative common ancestry that shares cultural symbols and practices (language, diet religion values and norms) perspectives that identifies differences between groups and a shared heritage. However, for this thesis, the definition of 'race' by Lee (2009), was adopted in order to assign each recruited individual to their respective population group, for example, White British, Chinese and Indians participants. These three races were chosen for this project because there were easily accessible at Staffordshire university. The recruitment process is further discussed in chapter 4, 5 and 6.

1.10 Aims

1. To develop cost-effective method for bare footprints collection and to compare the reliability of this new method to extant methods.
2. To recruit participants from three distinct races, White British, Chinese, and Indians method and sample their bare footprints
3. To investigate inter-race variations in bare footprints from the three races and develop new techniques to help distinguish and discriminate control bare footprints sampled from distinct races.
4. To investigate if bare footprint morphologies can potentially aid intelligence relating to how an unknown bare footprint could be classed as belonging to a certain race or individual 'who would most probably self-identify' as belonging to a certain race.
5. To establish a database using Microsoft Access software (version 365) for archiving control static bare footprint that allows new data to be added in from additional population groups

1.11 Objectives

1. To develop an electronic questionnaire and conduct a survey of the current methods and materials of gathering control bare footprints forensic podiatrists and bare footprints analysts (aim 1).
2. To develop self-evaluation questionnaires for participants to record demographic and biological data, for categorising geographical location and race (aim 2)
3. To develop alternative methods for control sampling of bare footprints, which are inexpensive and evaluate the method for robustness, repeatability, and reliability when compared to extant methods (aims 1 and 3).
4. To establish a prototype database using Microsoft Access Database software (aim 4).

1.12 Thesis Structure

This section presents the overall thesis structure and a brief description of each chapter. In total, this thesis consists of eight chapters each with different aims and objectives. The structure was chosen because it is appropriate for presenting the overall investigations, from the initial

investigation of a lotion which was first developed by (Bond 2013a), to developing a control sampling method for bare footprints using the materials suggested by Bond (2013a). This is followed by evaluating the method/materials on recruited participants, investigating the variations in bare footprints morphologies from the data gathered from the three populations groups, and finally establishing a database for future research work using the data. In addition, each chapter is also accompanied by a literature review and critical evaluation of each specific component.

Chapter 1 presents an introduction and theory, of which the thesis is founded, exploring the forensic analysis of bare footprints and the potential of bare footprints, marks or impressions in criminal casework. This chapter also presents some background information relating to evolution of the human foot and foot binding.

Chapter 2 consists of three pilot studies which present the development of a cost-effective method first developed by Bond (2013a) and investigates if the method can be adapted to bare footprints sampling. The first pilot study focusses on the development and testing the lotion to assess if applicable for sampling friction ridge skin. In addition, this pilot study examines the different lotion ratios to identify the optimum lotion suitable for capturing bare footprints. Pilot study one, also provides background information regarding how the lotion reacts with fax paper to develop footprints. The second pilot study presents a quantitative assessment of the lotion. This study investigates the lotion using a controlled sampling mechanism to assess the repeatability and reliability of the lotion using the fingerprint ink and the inkless shoeprint kit as standards. Furthermore, this chapter presents the statistical results of the comparative analysis between the proposed method and existing methods (which are currently used by forensic podiatrists), whilst critically evaluating the existing methods. The third pilot study considers the variables that affect control sampling of bare footprints and explores the remedies prescribed by the forensic podiatry community to develop a user-friendly and universal control sampling pad for use with the lotion.

Chapter 3 presents the findings of the survey which targeted forensic podiatry practitioners and academic researchers working with bare footprints. This chapter also presents a literature review of current methods and techniques used for capturing two-dimensional bare footprints.

Chapter 4 presents a comparative study between the lotion system and the inkless shoeprint kit. This chapter presents a literature review of the materials that are currently used by forensic podiatrists and/or bare footprints researchers to sample control bare footprints. In addition, this chapter presents some of the challenges of using the inkless shoeprint kit and the fingerprint ink. Furthermore, this chapter introduces the participant recruitment questionnaire used to capture biological and demographic data and sets out the minimum number of participants required to achieve a sample size with a power of $d = .8$ (large effect size), required for the subsequent population study.

Chapter 5 presents a reliability analysis of using the bare footprints lotion system. This chapter provides the researcher with a chance to investigate the comparability and reliability of the data gathered by two novice collectors using the same method and materials and compares the data to the data collected by the researcher (expert collector). This chapter investigates how knowledge, understanding and background of the novice collectors can impact the reliability and comparability of the control bare footprints sampled using the lotion system and a set of control sampling instructions. This investigation will also allow the researcher to understand if the proposed lotion system is robust and can be utilised by different individuals reliably before the lotion system is adopted for large data collection.

Chapter 6 is the main study of this thesis which investigates static bare footprints gathered using the lotion adopted from Bond (2013a). This chapter investigates the morphological variations of static bare footprints obtained using the methods developed in chapter 2 and 3. In addition, this chapter presents novel approaches to evaluating two-dimensional bare footprints and discusses the analytical approach employed in this chapter. SPSS, principle component analysis and model-based cluster analysis are used to investigate if there are racial differences influence by the bare-footprint morphology. The data analysed in this chapter was derived from linear measurements measured using the Reel method (Reel 2012), ratios and morphometric x and y coordinate data plotted along the weight bearing area outline of static bare footprints.

Chapter 7 this chapter present a literature review which introduces different types of database. This chapter presents the importance of establishing a bare footprints database and presents the benefits of such a repository for research purposes. This chapter also introduces the prerequisite of database design set out by the forensic science regulator (Tully 2018). Finally, this chapter

establishes a bare footprints database and present the database architecture to illustrate the relational tables contained within the database.

Chapter 8 summarises the main findings of the overall study and links all the chapters to the main aims of this thesis, demonstrating the contribution to new knowledge. This chapter also presents the recommendations and further work, for example, the importance of gathering additional data from other races. Finally, this chapter introduces the potential of machine learning and how the findings of the population study (chapter 6) could be used to create population specific shape templates capable of identifying race.

CHAPTER 2: Pilot Studies

2.1 Introduction

The previous chapter (1) provided some background information relating to forensic bare footprints analysis, the evolution of the foot, the structure of the volar skin and the different techniques that are currently used to sample and analyse bare footprints. The previous chapter also provided the definitions and distinctions between the fleshed foot and bare footprints, marks and impressions. In addition, chapter 1 showed how footwear choices and deliberate binding of the foot can alter the foot morphology. It was also important to highlight the traditional methods of analysing bare footprints and present new approaches currently employed by practitioners to provide the reader with some background information. Furthermore, the literature review in the previous chapter briefly highlighted how bare footprints analysis has evolved from pencil and straight edge ruler, to being analysed by computerised methods. The literature review also identified that, although there was evidence of research that had investigated the differences in foot shapes, from data gathered from different races, the findings of these studies were not applicable or could not be used to conclude that there were racial differences in their 'bare footprints'. This is because there are quantitative differences between the fleshed foot and their product, 'footprint/marks'. However, these studies play a vital role in supporting the notion that there are differences in foot shapes but, the question still remains, are the differences also apparent in bare footprints as well? Thus, to solve this question, large amounts of data would need to be generated using cost-effective methods. Currently, the most recommended materials (inkless shoeprint kit) by the forensic podiatry community for sampling control bare footprints are expensive to researchers with minimal cash to spend. Hence it was vital for this study to explore other affordable methods/materials that could potentially be adopted as alternative methods to generate large data sets cost effectively.

For this chapter, three pilot studies were conducted to achieve the overall aims and objectives of this chapter, which are outlined in section 2.2 of this chapter. The first pilot study was conducted to develop a formula / make-up of the lotion and to investigate the contrast using different quantities of ingredients thus to identify the optimum lotion ratios that facilitate the capture of good quality prints. Furthermore, pilot study 1 also presents the results of the different ratios of basic lotion to butylene glycol which were tested for optimum quality and contrast of the print. This was followed by pilot study 2 which was a quantitative based

investigation, between the lotion and the industry standard materials, for example, the inkless shoeprint kit and the fingerprint ink. Finally, pilot study 3 was conducted to identify the appropriate materials needed for a feasible delivery system (pad) and assess whether this could be adopted for control sampling as an alternative to the inkless pad.

2.2 Aims and objecteives

The overall aims of the three pilot studies were to develop a cheaper method for sampling control bare footprints. The second aim was to evaluate the lotion and compare this to existing industry standard methods which had been set as a benchmark. To achieve these aims, three objectives were set. The first objective was to develop the bare footprints lotion and evaluate the colour/contrast between the lotion, inkless shoeprint kit and fingerprint ink, using controlled laboratory conditions; followed by conducting a quantitative analysis between the lotion and the inkless system and fingerprint ink. Finally, these datasets will be used to create a delivery system which is suitable to use for gathering empirical data to assess whether this new approach could be adopted as a cheaper alternative for gathering control bare footprints.

2.3 Pilot study 1: Developing and testing the lotion

Fax paper or thermal paper contains leuco dye which reacts to protic solvents with a O-H bond in the side chain OH group (Bond 2013b). Thermal paper is widely used for producing receipts for our day to day transactions (Mendum et al. 2011). Thermal paper does not require ink to print, which has seen a rapid increase of its use and development of machines that use it (Bond 2013; Jasuja 2009). Thermal paper receipts are sometimes found at crime scenes containing latent fingerprints (Jasuja and Singh 2009). The methods needed to develop fingerprints on thermal paper are different to conventional methods required for developing fingerprints on ordinary paper. For example, when fingerprints are deposited on chemical free paper (ordinary paper), chemical treatment with ninhydrin petroleum or 1,8-diazafluoren-9-one (DFO) are the most appropriate for developing latent fingermarks. However, these methods are not suitable for developing latent fingermarks on thermal paper because they cause unwanted coloring of the leuco dye resulting in poor fingerprints (Jasuja and Singh 2009). Bond (2015) also indicates that, each batch of thermal paper is different to the next, for example, an investigation of different types of thermal papers acquired from four countries (the United States of America, china, the United Kingdom and Australia) all indicated that there were differences. According to Jasuja and Singh (2009), leuco dyes are colorless solids which change to become colored

when they come into contact with either components that accept electrons, such as oxygen and iodine, and heat. The oxidation of the leuco dye to produce a colored complex, involves opening the lactone ring structure which forms colored fluorine cation by extension of the conjugated double bond system (Figure 2.1).

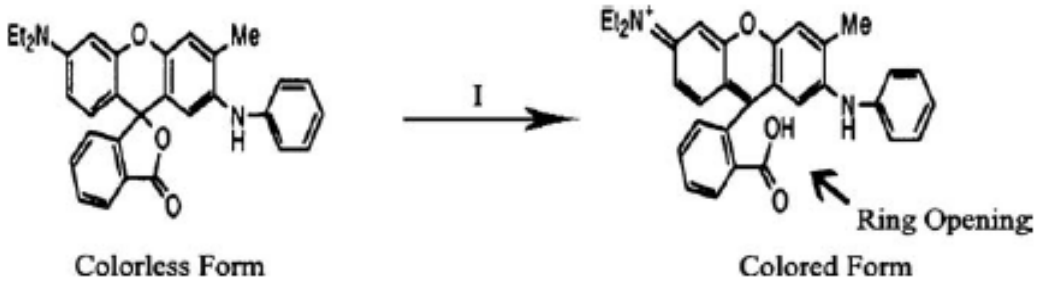

Figure 2. 1: Illustration of oxidation of the leuco dye to produce colored complex (Jasuja 2009)

After the reaction occurs and a print is developed, this will fade due to the lactone structure being reversible under basic conditions (Jasuja and Singh 2009; Bond 2015). According to Muthyala (2002), there are two types of dyes found in thermal paper. The first is leuco dye which produces a black color and the second is fluoran compounds which produces different colors when reaction occur, for example, brown, red, green, yellow and black. However, the idea of developing a cheap base lotion for capturing friction ridge skin was first conceived by Bond (2013a), who demonstrated that a protic solvent embedded in a base lotion could be used to capture fingerprints deposited on thermal paper. Bond (2013a), devised this method as a suitable alternative to black fingerprint ink, for capturing fingerprints from victims of crimes without causing further trauma to them, for example, the trauma on the victim, as a result of violent sexual assaults. Bond (2013a) also indicates that the cosmetic lotion does not dissuade donors from having their fingerprints recorded because of its composition, which simulates an ordinary base lotion contains no irritants such as those found in products like the inkless shoeprint kit which is regularly used for capturing bare footprints (Fisher and Scientific 2013). The main ingredients used to produce the lotion consists of glycerol, glyceryl stearate, cetearyl alcohol, ingredients which are generally found in cosmetic products and butylene glycol the reacting agent (Bond, 2013a). The lotion was developed by creating an emulsion and incorporating the reacting agent into a base hand lotion. The lotion was intended to act a delivery system for the protic solvent butylene glycol (reacting agent for leuco dye embedded in fax paper (Baron and Elie 2003; Bond 2013a). After developing the reagent lotion (bare

footprints lotion) using the original ingredients suggested by Bond (2013a), the lotion did not work well with the type of fax paper purchased for this project. According to Bond (2013a), each batch of fax paper is different, thus, the ratio of ingredients might need altering to acquire the right desired contrast. The type of paper that was purchased for this investigation was reacting with the lotion but, failing to develop into image that could be analysed in sufficient detail. This pilot study was conducted to develop and to assess which ratio of ingredients would be suitable for producing good quality contrast that is sufficient to be analysed.

2.3.1 Materials and Methods: Developing the lotion

Before experimental work was conducted, a disclaimer form was submitted to the university. The materials required to develop the bare-footprint lotion were sourced from Sigma-Aldrich United Kingdom, apart from the instruments used to create the emulsion. The ingredients consisted of 500 ml of triple distilled water, 200 ml glycerol, 30g of glyceryl stearate, 35g of cetearyl alcohol and 45 ml of the protic solvent butylene glycol. The instrument required to create the emulsion consisted of;

- 2x hotplates (Heating Magnetic Stirrer FB15001) manufactured by VELP Scientifica Europe
- 2x 76mm immersion thermometers (Min -10 ^{o}C – Max 110 ^{o}C) manufactured in the United Kingdom by Fisherbrand
- 1x total immersion Thermometer (Min -20 ^{o}C – Max 50 ^{o}C) manufactured in the United Kingdom by Brannan LO-*tox*^{TM}
- 2x 1000 ml glass beakers
- 1x hand-held blender (any blender could do)
- Ice in 3000 ml of water to maintain a temperature of -5 ^{o}C
- Heavy duty hand cleansers to wipe the hands.

To create the lotion, all the dry ingredients (30g of glyceryl stearate and 35g cetearyl alcohol) were put into a 1000 ml glass beaker, placed on a hot plate and dissolved in glycerol at 80 ^{o}C to form an oil phase. An additional 500ml of triple distilled water was decanted into a 1000 ml glass beaker and heated to 80 ^{o}C using a separate hotplate, to create the water phase. The butylene glycol (the reacting agent) was then added to the oil phase mixture, whilst maintaining the 80 ^{o}C temperature. The water phase at 80 ^{o}C was then added slowly to the oil phase while

maintaining 80 °C for both the water phase and oil phase. This process was conducted slowly in order to create an emulsion (Bond 2013a). The mixture was then whisked using a handheld blender whilst placed in a bath of iced water (-5 °C). The whisking continued until the mixture had cooled. After the mixture had cooled, the aqueous solution had transformed into the lotion. The final product was transferred into a dispenser pump for easy use.

2.3.2 Material and method: Evaluating the lotion for optimum contrast

To evaluate the lotion for optimum contrast, 9 pieces of thermal paper measuring ±16 cm x 16 cm (supplied by Stuart manufacturing) were sequentially placed onto the laboratory work top. A handheld pump dispenser containing the 150 ml of the lotion was used to dispense 0.5 ml of the lotion on to the palm. Using both hands, the lotion was gently rubbed on the hands, ensuring that the palm and fingers were evenly covered. Following the application of the lotion, the dominant hand (right) was firmly rested on the thermal paper, with its own weight, on the surface of fax paper 1 for ten seconds. The palm and fingers (friction ridges) were thoroughly cleaned using the heavy-duty hand cleanser wipes after each deposition. The application process was repeated each time with different increments of the butylene glycol per 150 ml of the standard reagent lotion. The ratio of the protic solvent butylene glycol: basic reagent lotion was altered from: paper 1 = 0 ml : 150 ml, paper 2 = 1 ml : 150 ml, paper 3 = 1.5 ml : 150 ml, paper 4 = 2 ml : 150 ml, paper 5 = 3 ml : 150 ml, paper 6 = 4 ml : 150 ml, paper 7 = 5 ml : 150 ml, paper 8 = 6 ml : 150 ml and paper 9 = 7 ml : 150 ml. Figures 2.2 to 2.10 illustrate the gradual introduction of different ratios of the butylene glycol into the basic lotion (containing only the quantities suggested by John Bond 2013).

2.3.3 Pilot Study 1: Results

The results presented below show the effect of different ratios of the lotion to butylene glycol on the 9 thermal papers used for this experiment (thermal paper 1 to 9). Once the deposition of the palm print onto the thermal paper was conducted, the 9 samples were left to develop for 30 mins before being photographed. As observed in Figures 2.2 - 2.10 below, 9 ratios of the lotion were investigated to assess the level of contrast. Each of the ratios indicated different results, from poor contrast to good contrast. Figure 2.2 shows thermal paper 1, sampled using the 0 ml : 150 ml ratio. It is clear from the visual inspection that the image lacks any colored pigments to indicate if any visual detectable reaction occurred between the of the leuco dye embedded

in the thermal paper and the basic lotion suggested by Bond (2013). The subsequent images demonstrate pigment developing after altering the original ingredients.

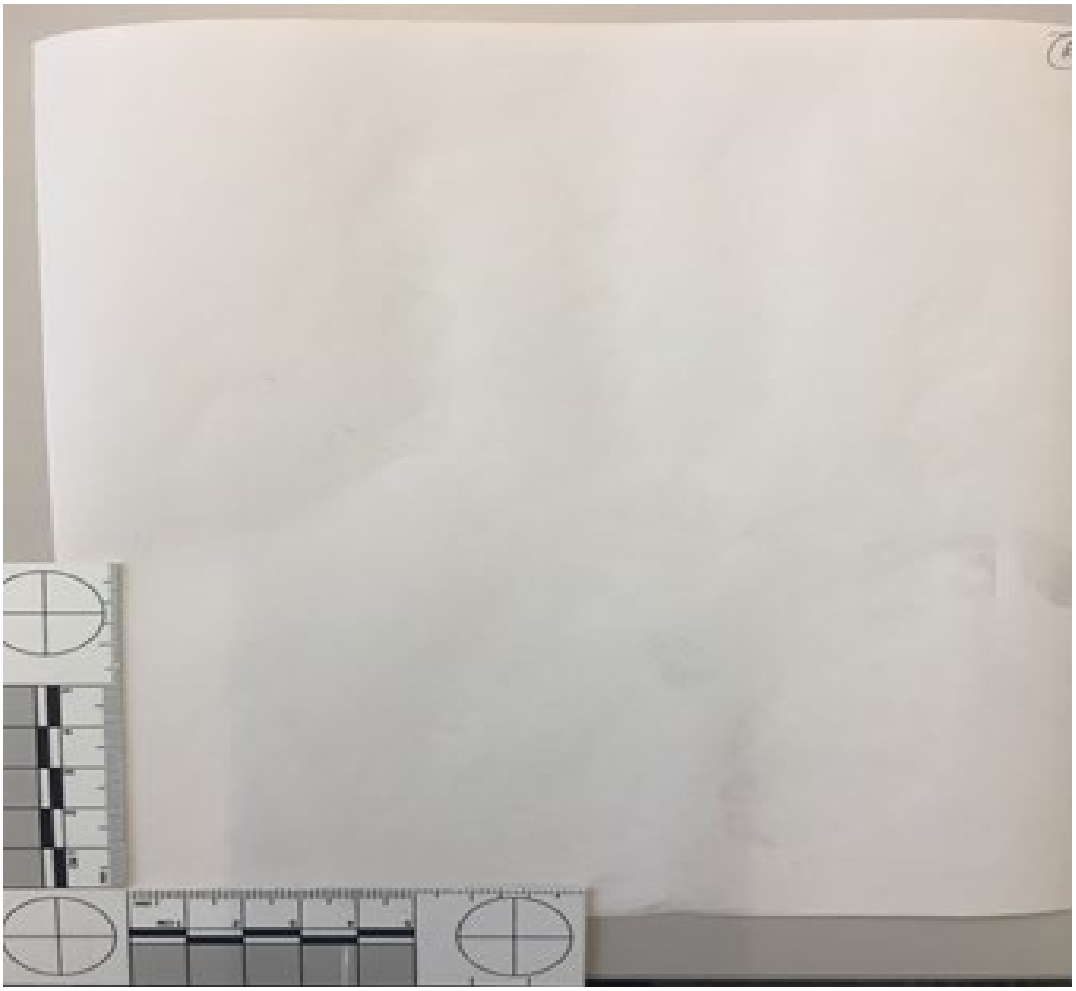

Figure 2.2: Indicating the level of contrast acquired, before altering the ingredients (0 ml : 150 ml)

Figure 2.3 indicates some slight colored pigments, demonstrating that altering the ratio by increasing the butylene glycol would start to cause the leuco dye to react, a result detectable by the naked eye.

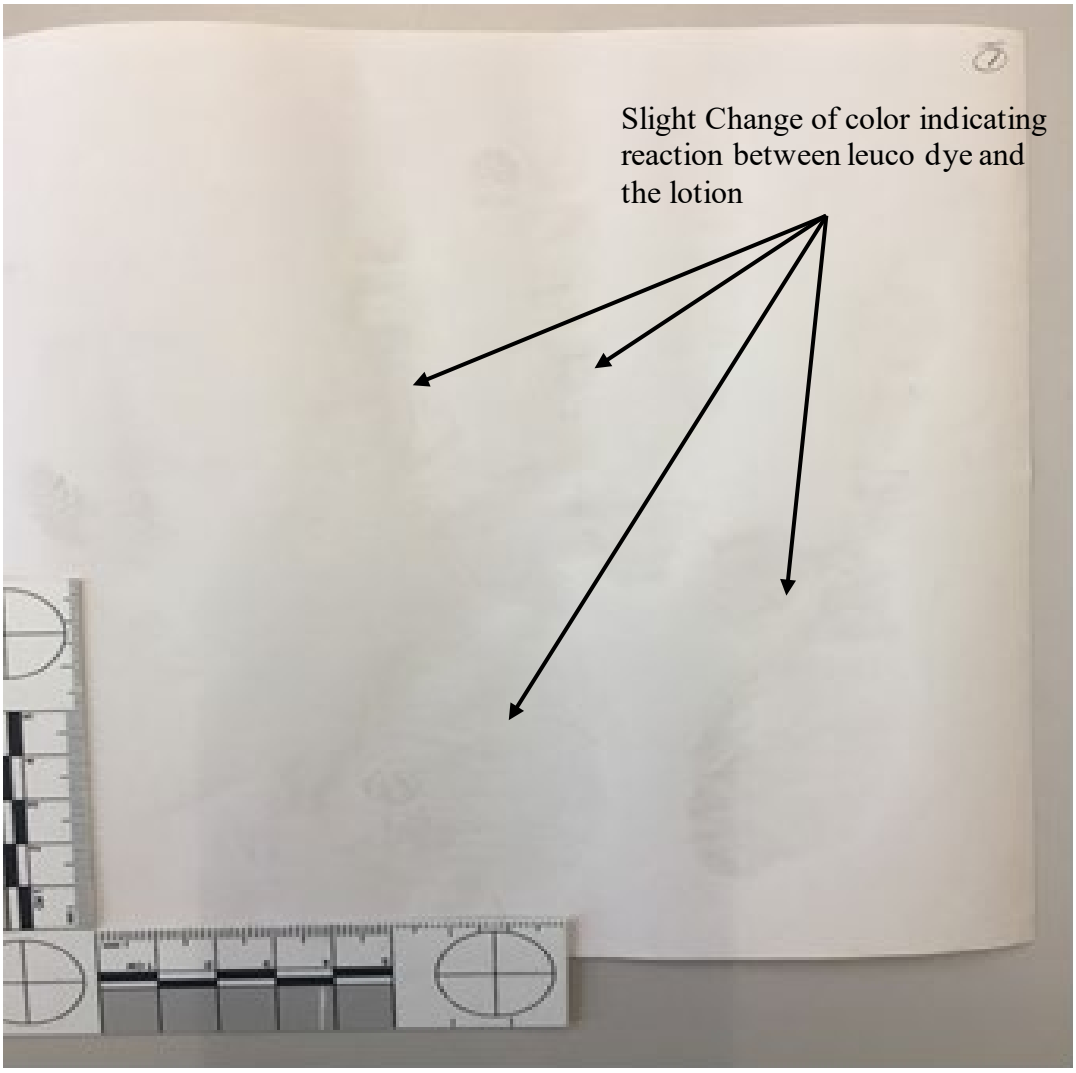

Figure 2.3: Illustration of the level of contrast after altering the ingredient ratios, to 1 ml of butylene glycol per 150 ml of the basic reagent lotion

Figure 2.4 indicates come parts of the palm and fingers which have reacted with visible coloured pigments developed. At this stage, it can be observed that the contrast has slightly improved, if compared to the previous ratios of 1 ml : 150ml (Figure 2.3)

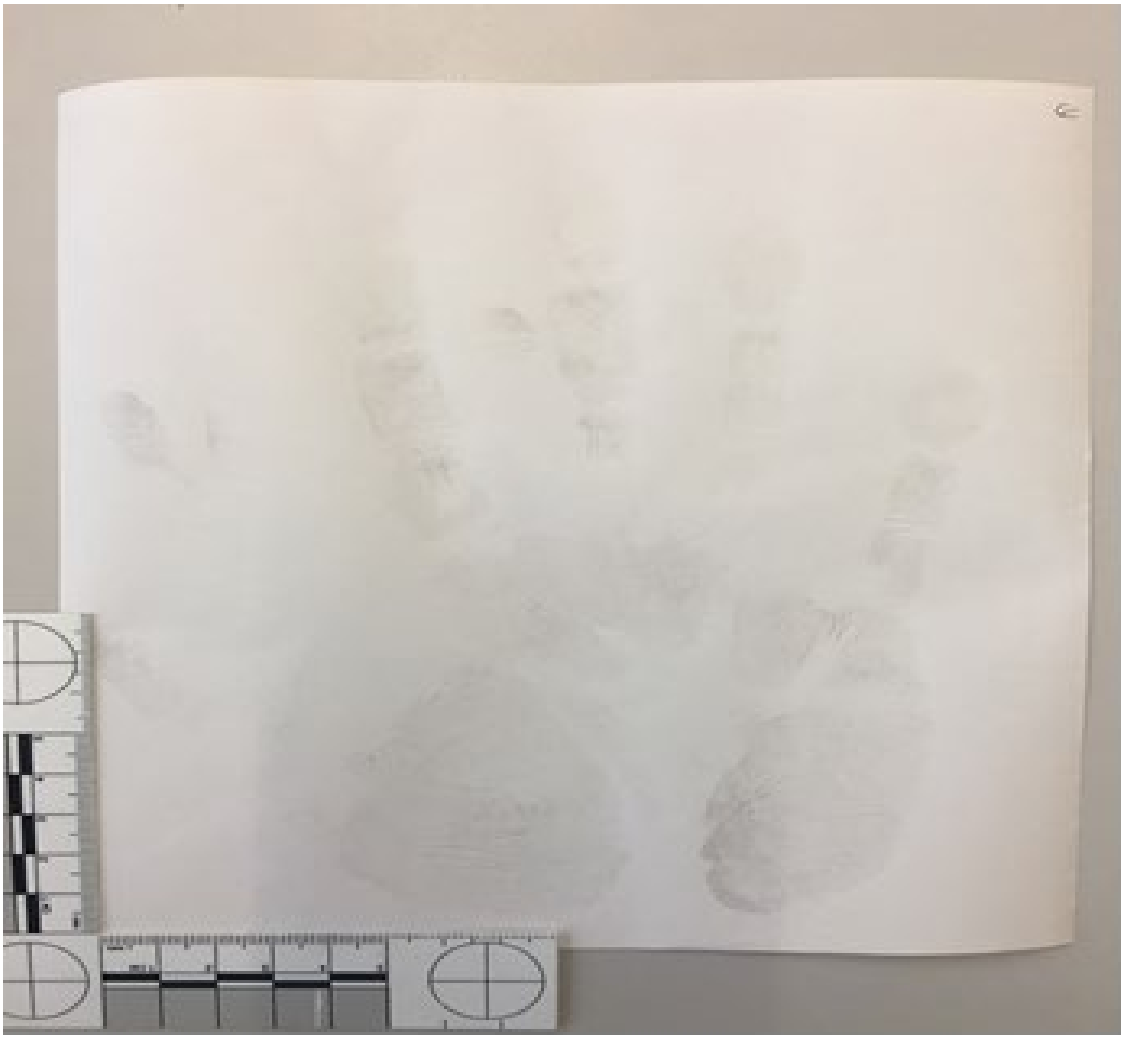

Figure 2.4: Illustration of the level of contrast after increasing butylene glycol to 1.5 ml per 150 ml of the basic reagent lotion.

Figure 2.5 indicates a continual improvement in the contrast which is attributed to the additional .5ml butylene glycol, from 1.5 ml :150 ml to 2 ml : 150 ml. Creases can be seen which were not previously apparent in Figure 2.4 or 2.3

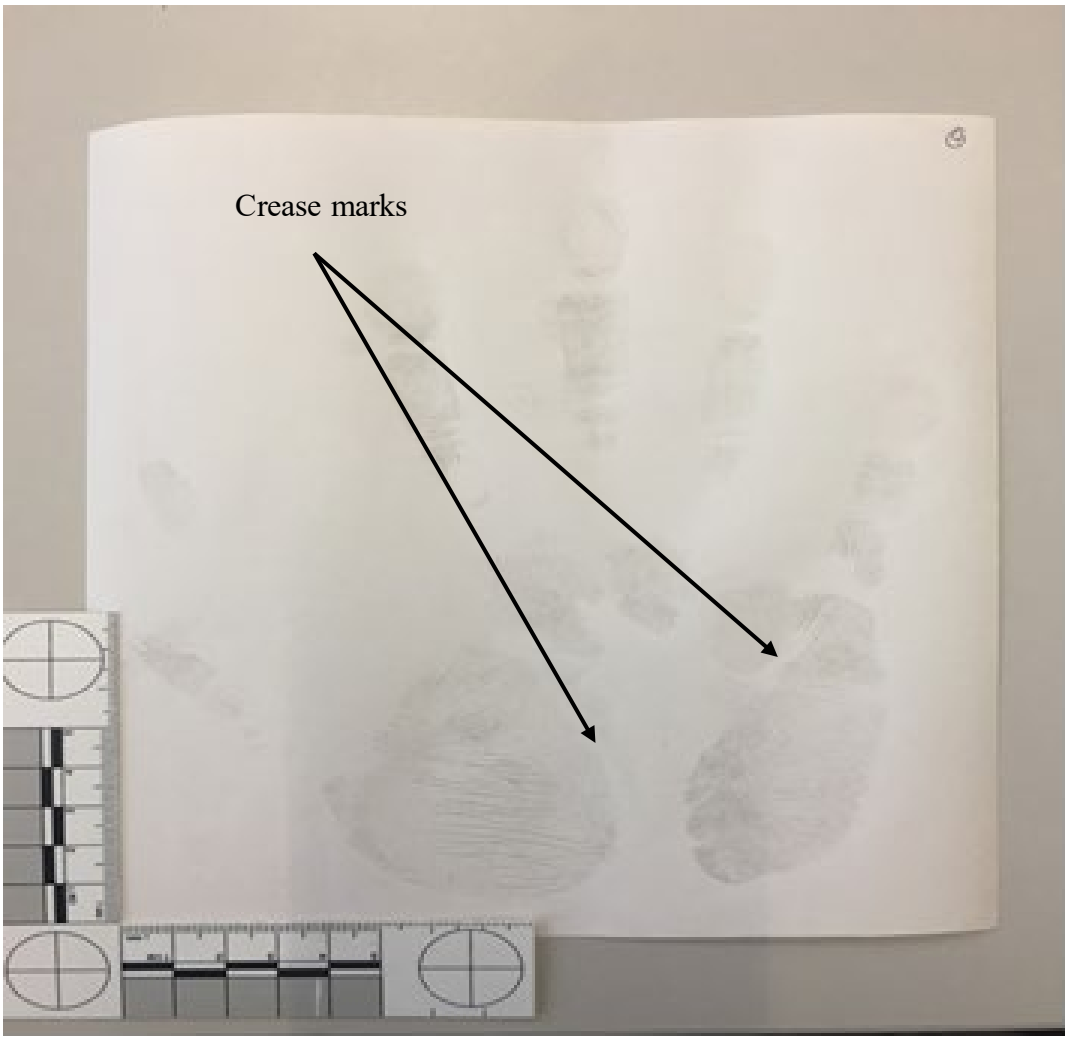

Figure 2.5: Illustration of the level of contrast after increasing butylene glycol to 2 ml per 150 ml of the basic reagent lotion.

Figure 2.6 indicates a dark palm and finger mark, an improvement from the previous ratios. The 3 ml : 150 ml ratio enable additional crease marks to be visible.

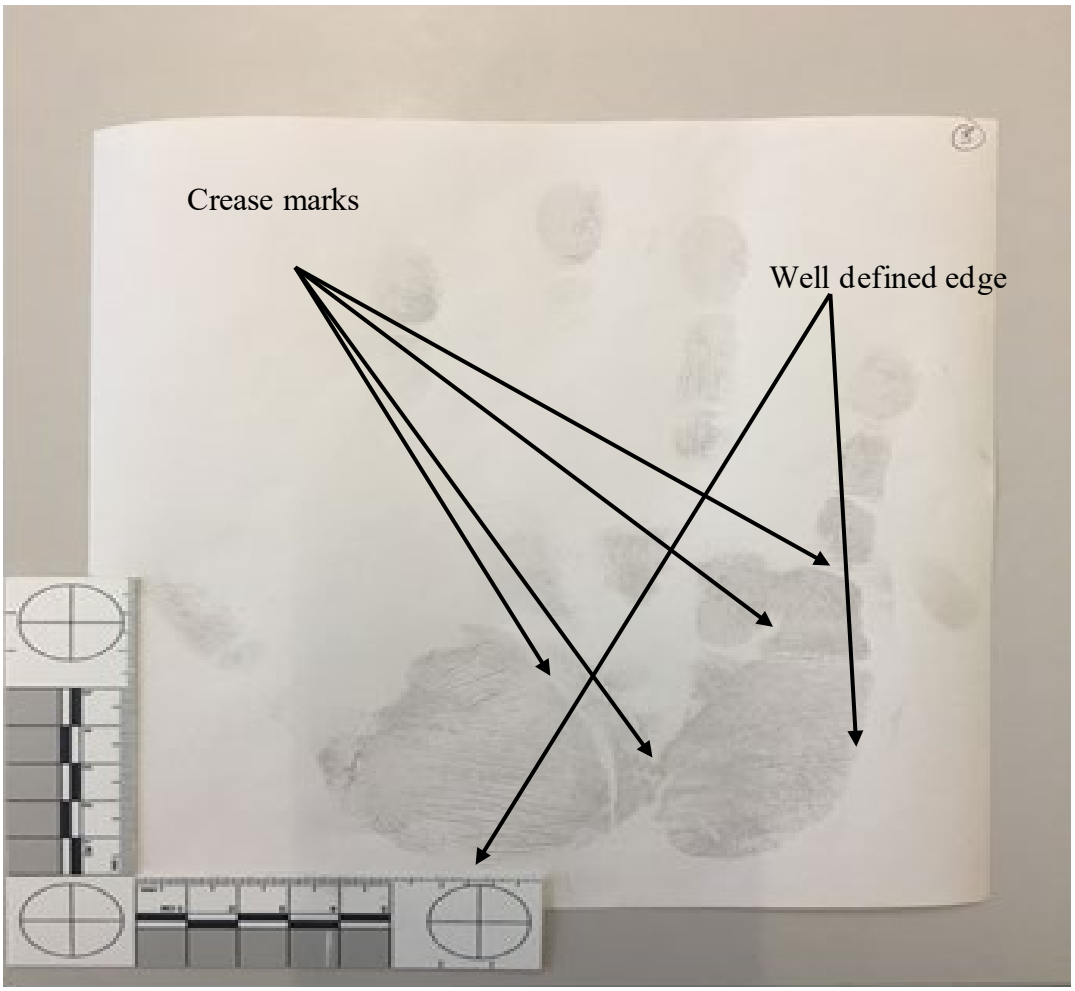

Figure 2.6: Illustration of the level of contrast after increasing butylene glycol to 3 ml per 150 ml of the basic reagent lotion.

Figure 2.7 indicates a much-improved contrast, which shows ridge marks and creases. At this stage, it is evident that increasing the butylene glycol to the basic reagent lotion improves the contrast.

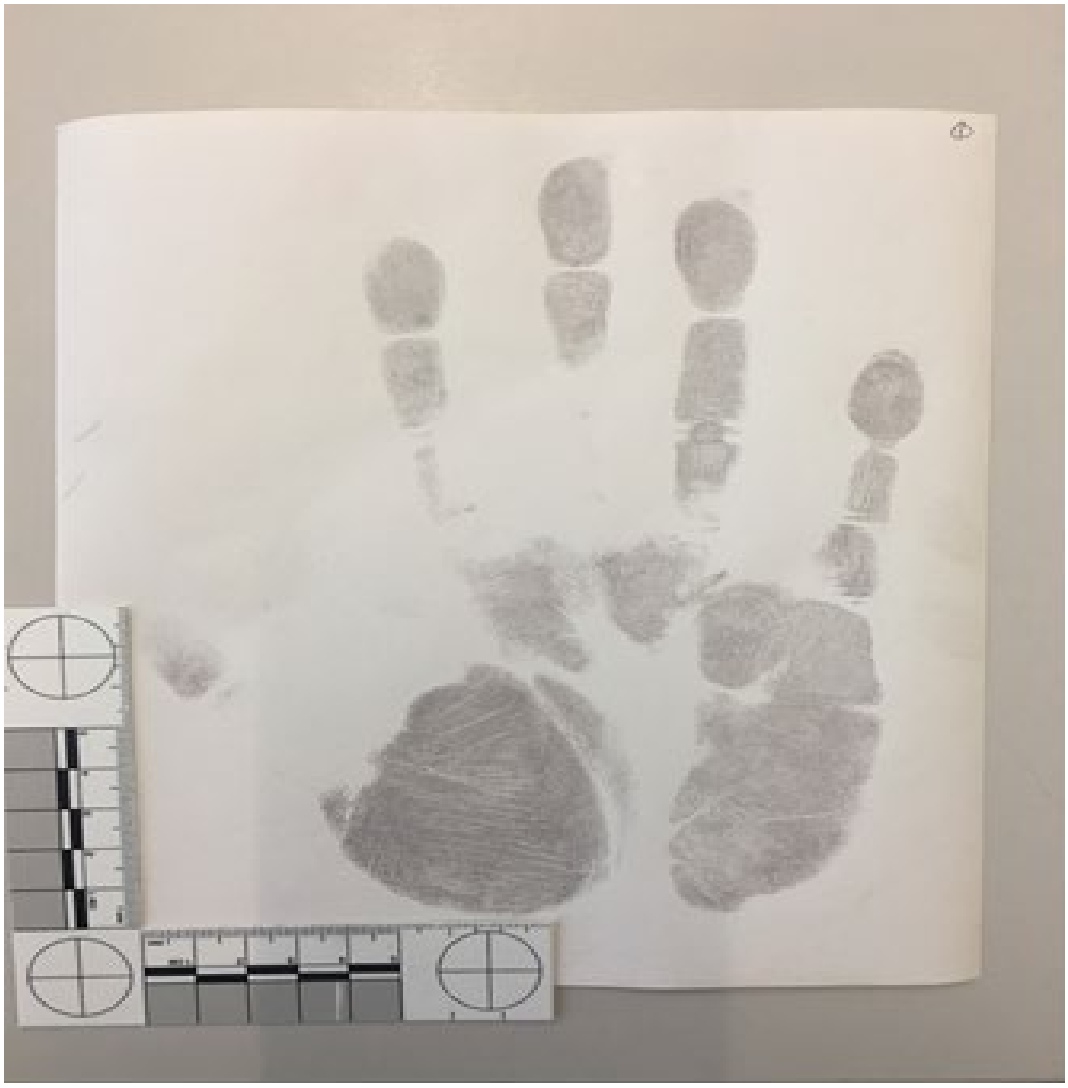

Figure 2.7: Illustration the level of contrast after increasing butylene glycol to 4 ml per 150 ml of the basic reagent lotion.

Figure 2.8 shows a much-improved palm and fingerprint, much improved if visually compared to all the ratios tested above. The edges are well defined, improved when compared to the previous ratios illustrated in Figures 2.7 – 2.2.

Figure 2.8: Illustration of the level of contrast after increasing butylene glycol to 5 ml per 150 ml of the basic reagent lotion.

However, once the ration illustrated in Figure 2.8 (5 ml : 150 ml) is exceeded by 1 ml, immediately after deposition the mark starts to fade. In addition, the edges are no longer neatly defined as previous observed in Figure 2.8.

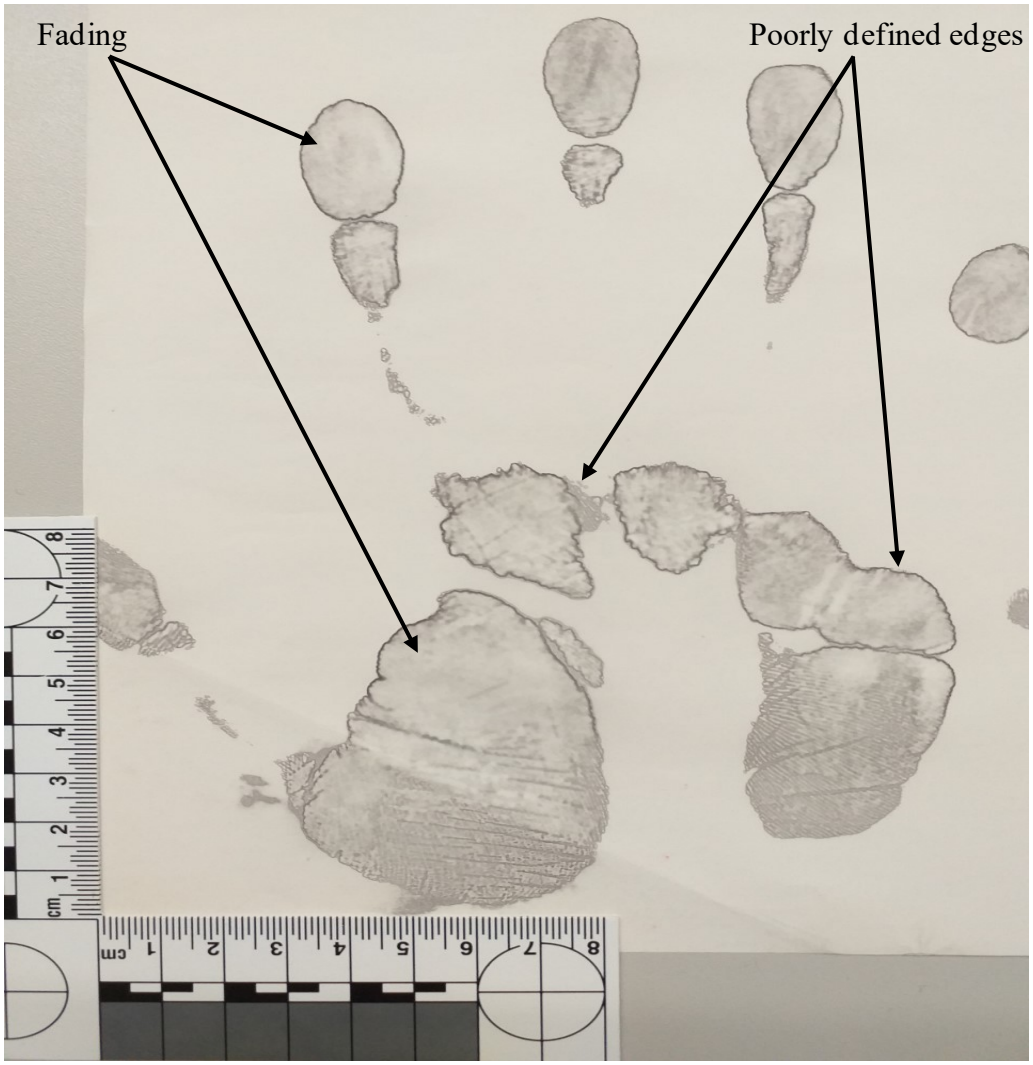

Figure 2. 9: Illustration of the level of contrast after increasing butylene glycol to 6 ml per 150 ml of the basic reagent lotion.

As the ratio is further altered beyond 5 ml : 150ml, the edges of the print continue to deteriorate. It is also clear that the palm area has faded and the outline is lacking a defined edge.

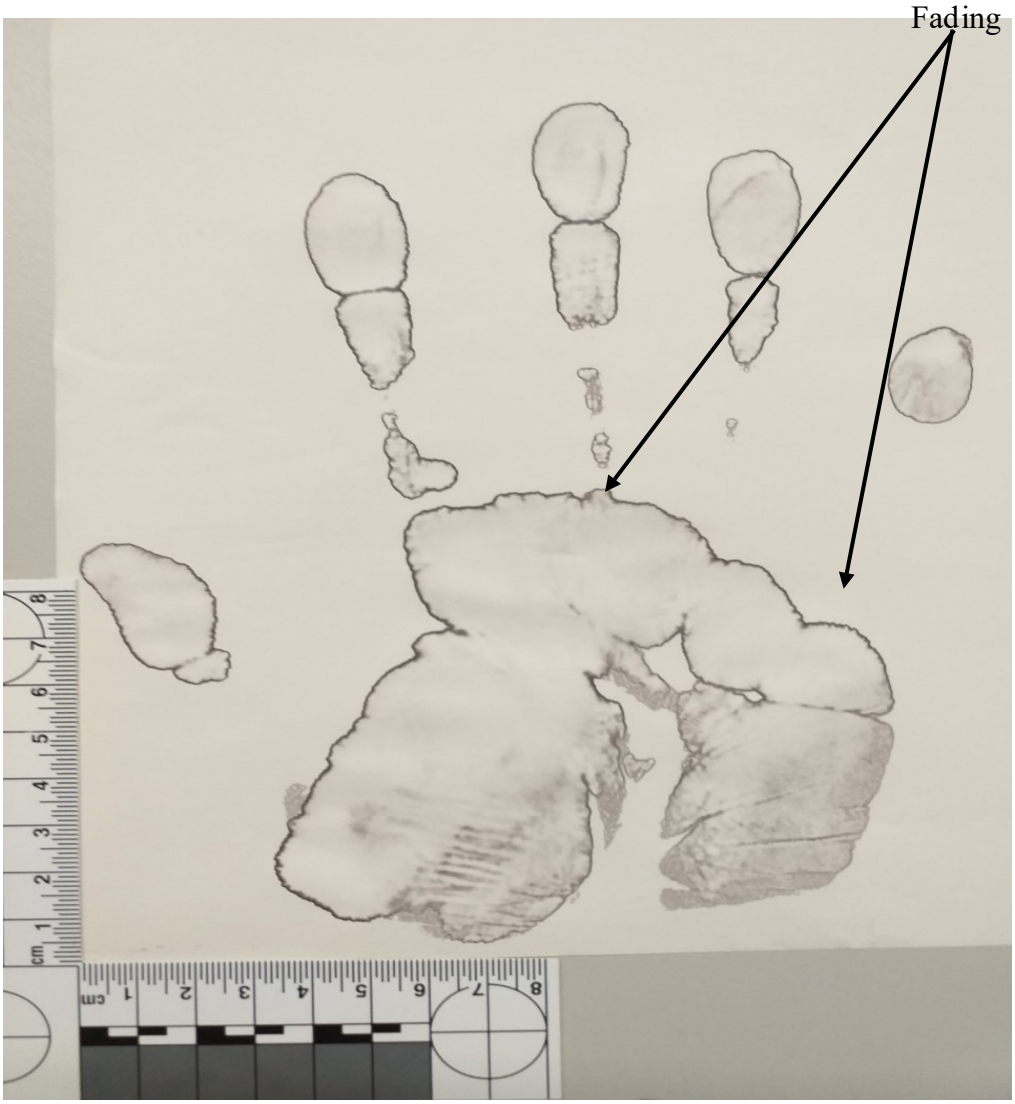

Figure 2. 10: Illustrates the level of contrast after increasing butylene glycol to 7 ml per 150 ml of the basic reagent lotion. This image also shows how increasing the ratio deteriorates the quality.

2.3.4 Pilot study 1: Discussion

For pilot study 1, 9 ratios were investigated to determine the optimum ratio for capturing volar skin ridge detail. The first stage of the investigation was to perform a qualitative assessment of the lotion. This study conducted an observational analysis to investigate if the contrast and morphological outline exhibited a high-darkened contrast, a clearly defined outline of the weight-bearing area. These characteristics were chosen because there are the same features that constitute a good quality bare footprint. For this study, palms and finger-marks were used as a substitute for bare footprints during the initial stages of the development of the lotion. The hand was particularly chosen because it was more practicable to use for assessing if features such as crease marks, presence of furrows, dermal ridges and weight bearing area were all being

retained on the thermal paper. Figure 2.2 illustrates the contrast observed after sampling the 0 ml : 150 ml lotion ratio, the sample did not exhibit any dark areas. For example, the dermal ridges and furrows were not clear, nor did the sample indicate a clearly defined morphological outline. Figure 2.2 lacked any colored pigments suggesting that a higher ratio would be required to trigger the color change. The lotion ratio was altered, 1 ml of the butylene glycol was incorporated in the 150 ml lotion. Figure 2.3 illustrates some slight changes compared to the print in Figure 2.2. For example, there is minimal contrast indicating some dermal ridges and furrows. At this stage of the investigation, the contrast was very poor. The ratio was altered to 1.5 ml : 150 ml (Figure 2.3), followed by 2 ml : 150 ml. Figure 2.4 indicates a significant change in contrast. However, even though the friction ridge detail is present, there is no clear quantifiable outline. The optimum contrast, which includes a clear outline, was reached when the ratio was further altered to 5 ml : 150 ml, please see Figure 2.8. following this, the ratio was further altered, which resulted in fading (2.9 – 2.10). At this point, it was realised that once the 5 ml : 150 ml ratio is exceeded, the quality of the print starts to deteriorate. Therefore it was identified that 5 ml : 150 ml ratio retained the contrast with no indications of fading. This ratio indicated in Figure 2.8, was repeatedly sampled for 5 times each, and each time producing consistent images. However, quantitative assessments will be conducted to assess it his ratio should be adopted for the remainder of the thesis.

2.4 Pilot Study 2: Quantitative analysis of the lotion

This pilot study adopted a metal flat plate and utilised this as the depended variable (DV) (metal sampler, Figure 2.8) to test three independent variables (IV) ((a) the lotion and thermal paper; (b) inkless shoeprint kit and treated paper; and (c) fingerprint and normal paper) The subject of interest in this experiment was the ability of the metal sampler to capture its true surface area (rectangle shape) using each of the independent variables. Most importantly, the metal control sampler was adopted because of its rigidity and applicability using all the materials, thus allowing the consistent capture of its true shape. There are similar experiments that have utilised non-bias objects (mechanical rig) to investigate variability, for example, the mechanical stamping rig designed to control the variability of pressure being exerted by the rig to test footwear (Farrugia et al. 2012). However, it is this notion of capturing consistent repeats, born from the Farrugia et al. (2012) study that enabled this pilot study to device the metal sampler as a control sample to investigate if the lotion is fit for purpose as an alternative to existing methods. The control sampler was adopted for this experiment as a means of

standardising and avoiding the discrepancies caused by the different application methods such as those observed in bare-footprint control sampling (Reel et al. 2010). Thus, allowing reproducibility across the experimental conditions. For this pilot study, the full length of control sampler for the right length (RL) and the top length (TW) measurements were the subject of interest. According to Thompson (1935) and Marsden (2011), that the essence of measurement at an operational level lies in the principle of standardization to allow units of magnitude to be consistent across experimental conditions. This implies that a regularity or stability of measures is required for there to be valid comparisons made across units of observations. (Please see Figure 2.8 for an illustration of the control sampler length = 195.2 mm; Width = 100 mm; thickness 10 mm; weight = 2.2 kg).

For this pilot study, there were three research questions set to investigate if the lotion and thermal paper were comparable to the industry standard. This study investigated if there was a difference in the measurement technique of sampling technique. The research questions for this study are listed below.

2.4.1 Pilot Study 2: Research Question

1. Is the lotion suitable for bare-footprint sample collection, as an alternative to the ink (inkless shoeprint kit) or fingerprint Ink?
2. Is thermal paper suitable for bare-footprint sample collection, as an alternative to the chemically treaded paper or normal paper?
3. Is there a difference in the measurement technique or sampling technique between all groups?

2.4.2 Null Hypothesis

- There is no statistically significant difference between the lotion, inkless shoeprint kit and fingerprint Ink.
- There is no statistically significant difference between thermal paper, treated paper and normal paper
- There is no statistically significant difference between lotion on thermal paper, inkless shoeprint kit on treated paper and fingerprint ink on normal paper

2.4.3 Alternative Hypothesis

- There is a statistical difference between the lotion, inkless shoeprint kit and fingerprint Ink.
- There is a statistically significant difference between thermal paper, treated paper and normal paper
- There is a statistically significant difference between lotion on thermal paper, inkless shoeprint kit on treated paper and fingerprint ink on normal paper

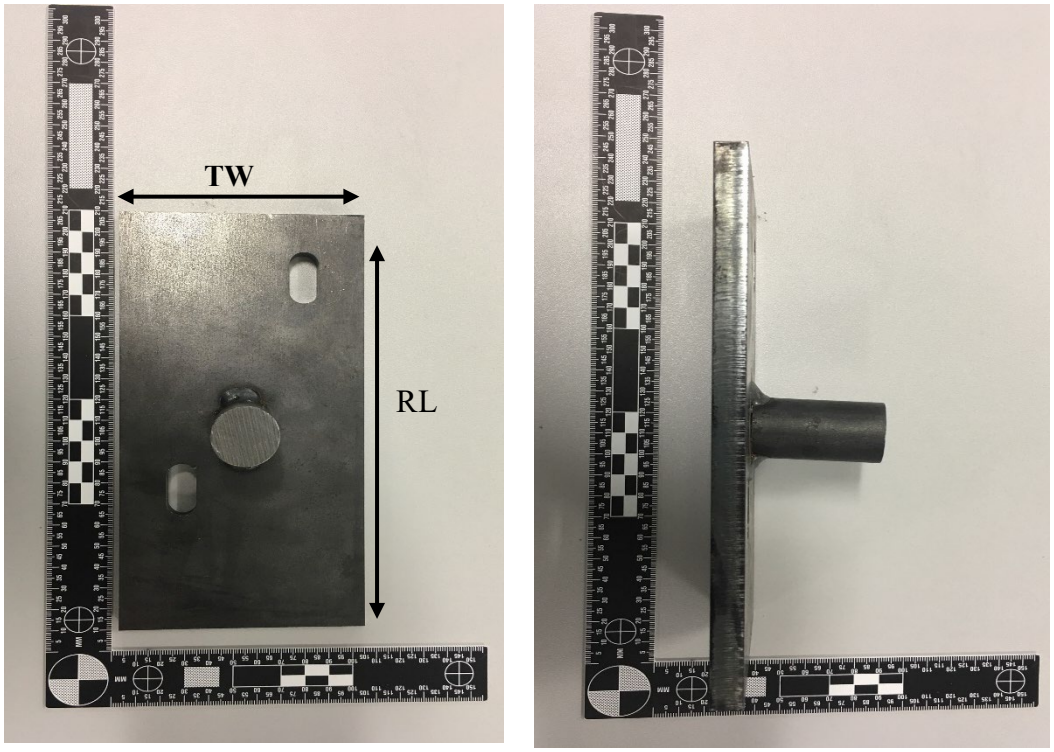

Figure 2.11: Illustrates the control sampler used as the dependent variable to acquire quantitative data for pilot study 2. TW denotes to top width, and RL denotes to right length. All the lengths were measured in millimetres (mm)

2.4.4 Pilot Study 2: Materials and methods

The materials used for this pilot study included; 1 tube of fingerprint ink, 1 inkless shoeprint inkless kit (supplied by CSI Equipment), the lotion in a 500ml pump dispenser; 25 inkless ink recording sheets (Treated paper), 25 normal paper measuring 170 mm x 350 mm, 25 Stuart manufacturing fax paper measuring 30 mm x 210 mm, a mini sleeve roller brush measuring 102 mm with 3 sleeves (one for each experimental condition), 1 standard laboratory timer,

heavy duty hand cleansers (wipes), a computer equipped with GIMP GNU Image Manipulation Program (Software Version 2.8.16) and statistical package (IBM SPSS Software Version 23), 1 flatbed Scanner with minimum optical resolution 150 dpi and a metal flat plate used as a control sampler (length = 195.2 mm; Width = 100 mm; thickness 10 mm; weight = 2.2 kg) (Figure 2.8) and finally 3 disposable roller brushes to evenly distribute each of the three substrates onto the control sampler. To generate the data, a repeated measures design experiment was conducted, the first control samples were generated using lotion/thermal paper, followed by the inkless shoeprint kit/treated paper and lastly fingerprint ink/normal paper. To begin sampling the lotion, 25 pieces of thermal paper were placed flat onto the laboratory worktop next to each other sequentially. The roller brush was pre-loaded with 10 ml of the lotion, then rolled onto the control sampler under-surface using an up – down motion. Immediately after, the sampler was placed on the first sheet for approximately 30 seconds and allowed to rest on its weight before being lifted off, followed by loading the roller brush again (with the lotion), and then placing it on the next sheet for 30 seconds. Soon after lifting the control sampler from the sheet, the chemical reaction between the leuco dye and the lotion could be observed taking effect. This process was repeated on each of the thermal sheets until the remaining sheets had all been recorded. The sampler was cleaned each time after each deposition using heavy duty hand wipes. For sampling the inkless shoeprint kit on treated paper, 25 recording sheets of treated paper were placed flat onto the laboratory worktop next to each other sequentially. This was followed by rolling the brush (equipped with a fresh sleeve) onto the inkless pad (to initially collect the inkless ink residue) before rolling the brush (containing the inkless residue) onto the control sampler; immediately after, the brush was rolled (using an up – down motion) on the control sampler under-surface, before placing the control sampler on the treated paper sheet for approximately 30 seconds each time (allowing the sampler to rest on its weight), before being lifted off. This process was repeated on each of the treated paper sheets until the remaining sheets had all been recorded using the inkless shoeprint kit. For sampling the fingerprint ink, 25 sheets of normal were placed flat onto the laboratory worktop next to each other sequentially. About 5 ml of the fingerprint ink was loaded onto a fresh roller brush sleeve and transferred onto the control sampler under-surface using an up – down motion. Immediately after, the control sampler was placed on each sheet for approximately 30 seconds and allowing the sampler to rest on its weight, before being lifted and the same process being repeated for the remainder of the sheets. This process was repeated until all the sheets were recorded.

2.4.5 Pilot Study 2: Statistical analysis

The power of the sample size for this experiment was calculated using the G-power software version 3.1.9.2, obtained from http://www.gpower.hhu.de. This software was used to calculate and identify a sufficient sample size that would allow hypothesis testing (Faul et al. 2007). The G-power effect size calculator was set to identify an appropriate sample size with a power of at least 80% or above (d = 0.8) (Cohen 1992). According to Rosenblatt (1955), a sample size with a power of d = .8 (large effect) is sufficient for hypothesis testing. Cohen (1992) indicates that the values of effect sizes are classed into three conventional values. These values are calculated as small (d = 0.2), medium (d = 0.5) and large (d = 0.8). Thus, this experiment utilised 25 repeats per sampled group, which meant that an inference to the greater population is comprehended (Cohen 1992; Field 2013). For example, the larger the sample size, the smaller the margin of error and the smaller the sample, the bigger the margin of obtaining a type 1 error

For this investigation, the measurement of the diagonal length was adopted for this study. The right length (RL) and the top width length (TW) measurements were used to calculate each independent variable. For example, the formula a^2 (RL) + b^2 (TW)= c^2, was used to create the new variable (diagonal) (Figure 2.8 which shows the control sampler used to acquire quantitative data for this pilot study). These diagonal measurements were chosen to investigate if any spread of the substrate breached the limit set by the control sampler on both x-axis and y-axis of the paper. The data for this experiment was analysed using SPSS software version 25. The statistical design utilised to analyse the data, is that recommended for statistical analysis of forensic evidence (Zadora et al. 2014). The data was first explored to ascertain its level of distribution using the Q-Q plots and histograms. These plots were constructed to provide the researcher a visual representation of the distribution of data. Additional histograms were also used to assess the distribution of data. According to Field (2013), normally distributed data would entail that data points follow or form a straight line (dots along the line). For quantifying the data distribution, the Shapiro-Wilk's test was used to assess if the data had deviated from a normal distribution. The assumptions of normality using the K-S test and Shapiro-Wilk's test, allows for identifying correct statistical tests that are fit for purpose (Field 2013). The mean values of the 4 experimental levels, control sampler and the three substrates (lotion, inkless and the fingerprint ink) were also assessed using a box and whisker plot, before analysing the data using a One-way ANOVA to compare the means of the sampler and the three substrates.

2.4.6 Pilot Study 2: Results and discussion

The data was explored in SPSS and the descriptive statistics of the means, minimum, maximum, standard deviation range and skewness (Table 2.1).

Substrate	Mean (mm)	Minimum (mm)	Maximum (mm)	Std. Deviation	Range	Skewness
Sampler	219.13	219.0	219.4	0.0894	.4	0.760
Lotion	218.87	218.7	219.2	0.154	0.5	0.634
Inkless	218.87	218.7	219.3	0.1717	0.6	0.904
Fingerprint	218.89	218.5	219.2	0.1995	0.7	0.098

Table 2. 1: Descriptive statistics for the three substrates: Lotion (n = 25), inkless ink (n = 25), and fingerprint ink (n = 25)

For this experiment, the values were not rounded because it was important to detect if the lotion method is sufficiently accurate to be fit for purpose or comparable to the industry standard methods (fingerprint ink and the inkless shoeprint kit). The sampler recorded a mean that was slightly higher when compared to the three substrates. However, this is insignificant given that all measurements were within 0.30 mm. The mean difference between all the substrates indicate that the true surface area of the control sampler was retained. The standard deviation values were small, suggesting that there was repeatability on all substrates (lotion, inkless and the fingerprint ink). This result is significant because it demonstrates that all mean values and standard deviation values are not significantly different. Field (2013) and David et al. (1954), indicate that when the standard deviation is closer to zero, the mean value is well represented by the data. The inspection of the bar graph indicated that the difference between the substrates was not substantive to suggest there is a difference (Figure 2.12).

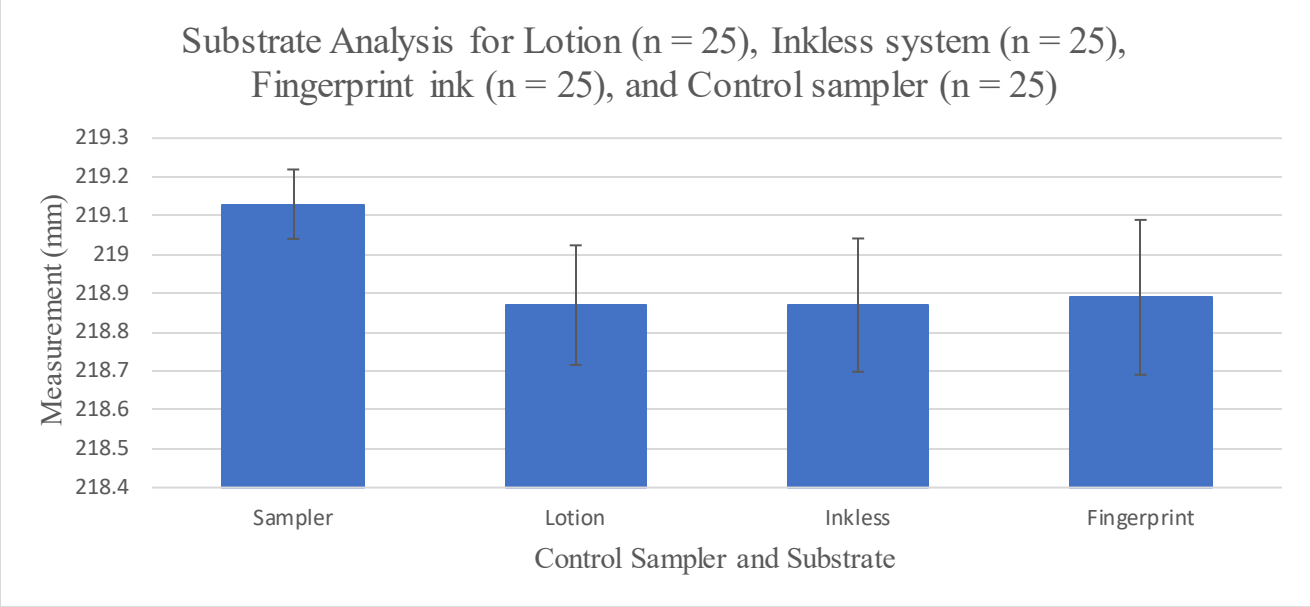

Figure 2. 12: Chart illustrating the results of the four experimental levels, the control sampler and the three substrates (lotion, inkless and the fingerprint ink)

The Shapiro-Wilk test indicated that all measurements were normally distributed ($p > 0.05$), suggesting that the assumptions for conducting a one-way analysis of variance (ANOVA) were justified. According to Field (2013), the Kolmogorov-Smirnov test and the Shapiro-Wilk's test are best for detecting if the data deviates from a normal distribution but, the Shapiro-Wilk test is more powerful at detecting differences from normality. Field (2013), also indicates that the Shapiro-Wilk test yields exact significance values, whereas the Kolmogorov-Smirnov test only provide an approximation for the significance.

According to Kucuk et al. (2016), a one-way ANOVA is suitable for comparing the differences between several independent groups of data. Conducting a *t*-test would only be appropriate if there were 2 groups but for more than 2 groups, carrying a series of *t*-tests to analyse three or more experimental conditions would increase the chance of a type 1 error from the .5% value to unacceptable levels (Field 2009; Kucuk et al. 2016). The one-way ANOVA only highlights if there is a difference between the groups of data but does not show the exact location of the difference, thus post-hoc tests such as Tukey test would be used to further investigate the data to identify where the data deviated (Field 2013). The one-way ANOVA indicated that there was a statistically significant effect at the $p < .05$ level between the four groups (F (3, 96) = 16.006, p = 0.000). The post hoc test was conducted and the Tukey HSD test indicated that there was no statistically significant effect between the three substrates, lotion (218.871 ± .1540 mm, p = 1.00), inkless ink (218.871 ± .1717 mm, p = .921) and the fingerprint ink (218.899 ±

.1995 mm, $p = .922$), however, there was a statistically significant effect between the control sampler ($p = .000$) and all three substrates. According to Brown, (2005), Tukey's HSD test is designed to conduct pair wise comparisons of means, whilst maintaining the error rate of the pre-established alpha level. The statistical results indicate that there is accuracy in the sampling technique, indicating repeatability and comparability between the three substrates. The difference between the three substrates is not substantive to render the lotion as inaccurate, but instead illustrates that there is conformism between the lotion and the industry standard methods (inkless ink and fingerprint ink). However, the descriptive statistics produced by the sampler were as expected, for example the sampler to differ from the three substrates because of the layer introduced onto the sampler surface. It is evident that the substrate layer did contribute in some way positively or negatively to the overall dimensional value of the substrates. The control sample mean value (M = 219.133mm) indicates that there was a mean difference of 0.262 mm with the both the lotion and the inkless ink. In addition, there was also a mean difference of 0.234 mm between the control sampler and the fingerprint ink. To conclude, these mean differences are small and therefore not substantive. Therefore, the sampling technique and measurement technique are both accurate. The overall pilot study demonstrates that the three substrates can be used interchangeably.

2.5 Pilot Study 3: Designing the Control Sampling Pad for the Lotion

Before trialling the control sampling pad, the lotion was first tested using the hand application (Figure 2.13 and 2.14). The hand application method involved rubbing a small amount of the lotion on the palms, then transferring this thin layer of lotion onto the foot undersole. This pilot study was mainly conducted to assess if the hand application method could be adopted to capture control dynamic bare footprints. Figure 2.9 and 2.10 illustrate the hand application method. During the pilot study, it was identified that the lotion was causing slippage when being applied to the foot. This impediment produced distorted control bare footprints. Following this, it was decided to only sample static bare footprints.

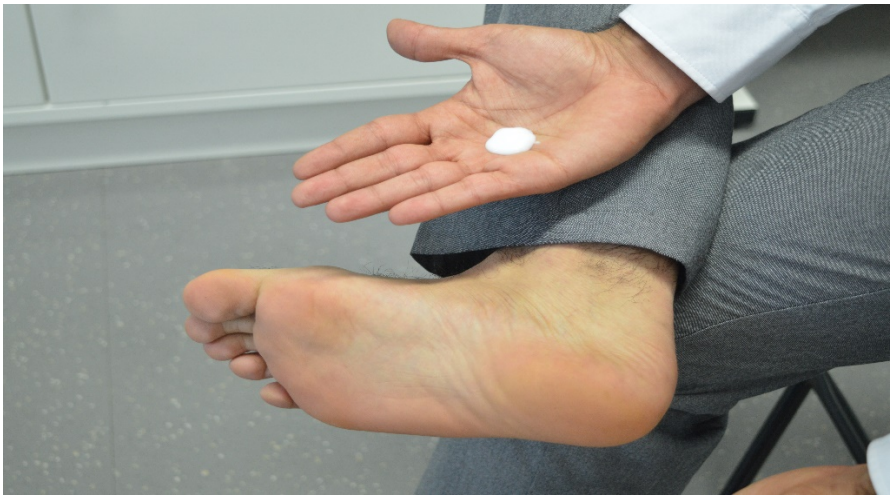

Figure 2.13: Application of the lotion using the had whilst sitting (step 1)

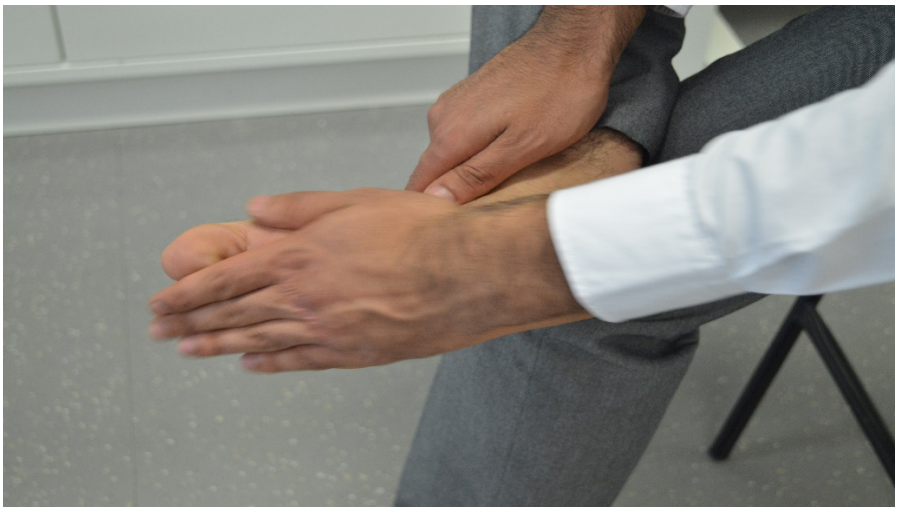

Figure 2 14: Application of the lotion using the hand whilst sitting (step 2)

This process required a small amount of the lotion to be placed on to the palm of the hand. This was then gently rubbed on/into the furrows and dermal ridges of the friction ridge skin and all over the weight bearing area of the foot. The participant then stood upright and walked on a role of thermal paper to deposit bare footprints.

Figure 2.15: Walking on a roll of fax paper to capture dynamic bare footprints (step 3)

2.5.1 Pilot Study 3: Methods and Materials for Designing the Control Sampling Pad

The pad was created based on the past study with demonstrated slippage. The pad was made from chamois leather measuring 40 – 42 cm in length by 20 – 22 cm in width (Figure 2.12) and stitched to a nonporous compound plastic sleeve to prevent unnecessary movement during sample collection (Figure 2.13).

Figure 2.16: Illustration of the chamois leather before being stitched in to the nonporous sleeve.

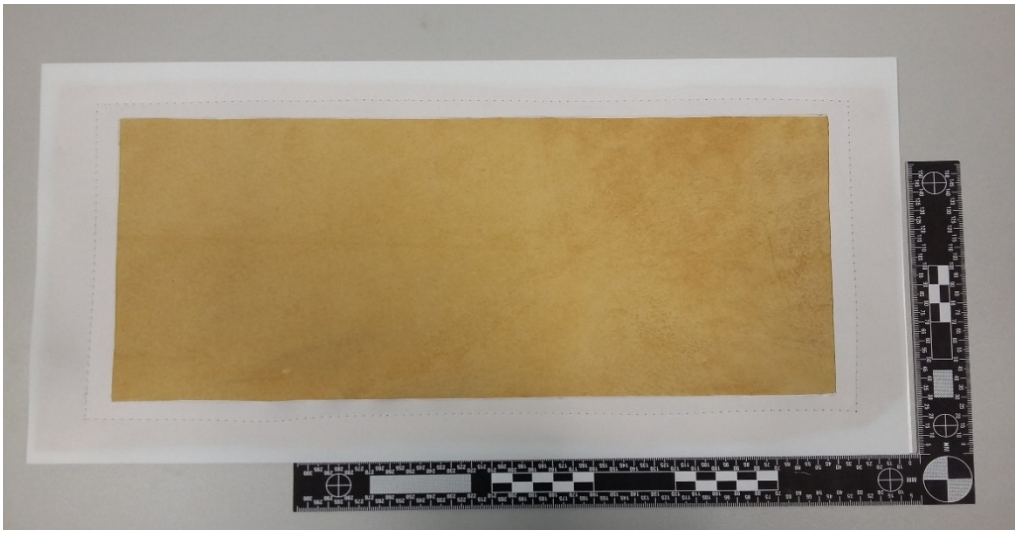

Figure 2. 17: Illustration of the chamois leather pad stitched onto a nonporous sleeve

2.5.2 Pilot Study 3: Discussion: Designing the Control Sampling Pad

It was soon discovered that some of the lotion ingredients, like the glycerol and butylene glycol were causing slippage. This problem was observed when the researcher was attempting to capture dynamic footprints. Nonetheless, using a roll of fax paper also meant that much of the lotion that was initially rubbed on the undersole was lost before a reasonably good quality bare footprint could be captured. This was caused by the depletion of the lotion, becoming less and less due to locomotion. Furthermore, during the preliminary experiments it was also discovered that, when trying to stand erect with both feet on the laminate floor to capture static bare footprints, the oil in the lotion was affecting balance. According to Naples and Miller (2004), a slippery floor can potentially result in distorted footprints. It is also indicated by Monaco et al. (2017) that, in order for the human body to sustaining balance and postural control, the body would need to implement sophisticated motor control strategies to prevent falling, hence, affecting the outcome of the control footprint. Consequently, collecting data using this approach resulted in data that was unusable, samples which mostly exhibited smudges. It was also evident from the recorded samples that there was a lack of consistency in the quality between the repeats. For example, the contrast and the overall outline of the footprint between the samples. In addition, the lotion quantity used in the hand application could not be regulated easily. For instance, putting too much lotion on to the foot led to distorted bare footprints or

applying small amounts of the lotion led to poor quality bare footprints, due to the lotion being lost on to the floor. This is a disadvantage when compared to the inkless system which allows optimum quality dynamic bare footprints to be captured. Due to these findings, the hand application method was abandoned. The discovering of this problem enabled the researcher to try different types of materials to create a control sampling pad. To develop the pad, various fabric materials which include polyester, natural cotton cloth, and chamois leather were investigated. All these materials were investigated, each in the same manor that an inkless pad is used. The chamois leather pad proved that it could produce an output not so different (quantitatively) to the inkless shoeprint kit, thus allowing comparability. Further details of how the pad was used are presented in chapter 4 (section 4.3.2), where participants volunteered to have their bare footprints recorded using the lotion and pad. It was important to ensure that whichever material was adopted can facilitate the capture of two-dimensional static bare footprints.

2.5.3 Summary of key findings

The three pilot studies were designed to develop a bare footprints sampling method which is more cost effective in comparison to existing methods and generally acceptable to the population, due to its non-toxic nature.

Pilot study 1

The results from Pilot Study 1 suggested that that the 5ml per 150ml of the basic reagent lotion was the optimum ratio that produces a good quality print. It was discovered that if this ratio was exceeded, for example, 6ml per 150ml or 7ml per 150ml the mark starts to fade. In addition, any mark produced with a ratio below the 5ml per 150ml resulted in mark that was poor in quality.

Pilot Study 2

Pilot Study 2 was conducted to investigate the reliability of using the lotion for bare footprint analysis. The result of this investigation indicated there was a statistically significant difference between the control sampler, lotion, inkless system and the fingerprint ink. But, when a post-hoc study was conducted to investigate where the difference was, the results suggested that the three substrates were comparable, and recording six repeats of control samples is appropriate because this allowed for the average and spread of the data to be known.

Pilot Study 3

After developing and testing the lotion, a delivery system was required to enable sampling of bare footprints that are comparable to samples recorded using current industry standard methods. The hand application was tested first for sampling dynamic bare footprints and it was discovered that the glycerol and butylene glycol were causing slippage which resulted in distorted bare footprints. This approach was abandoned for a more conventional design that mimicked the inkless system. For designing the pad, various fabric materials were tested, for example, polyester, natural cotton cloth and chamois leather. The best results were produced by the chamois leather. The chamois pad was adopted for the remainder of the project.

2.5.4 Conclusion

One of the goals for conducting the pilot studies was to develop a pragmatic method for gathering large datasets of control bare footprints using cheap materials. The outcome of pilot study 1 led to the successful develop the lotion, capable to be used for capturing two-dimensional bare footprints. After investigating the different ingredient ratios of the lotion, from the basic lotion 0 ml : 150 ml to the 7 ml : 150 ml, it was identified that the 5 ml : 150 ml ratio was the most practicable ratio to adopt for the entire project. Following this study, pilot study 2 was conducted to assess the accuracy of the lotion method, by conducting a comparative study between the new sampling method and the industry standard methods (fingerprint in and the inkless ink) currently used by forensic practitioners. The four groups of data were analysed using a one-way ANOVA which revealed there was a statistically significant effect between the four groups ($p < .05$). Following this, post hoc tests were conducted and the results of the Turkey's HSD test revealed that there was no statistically significant effect ($p > .05$) between the sampling method but, there was a statistically significant effect ($p < .05$) between the control sampler and the three sampling methods. After further investigations, it was identified that the difference was very small, therefore not substantive, given the amount of variance in the mean values combined (between all groups) which were ± 0.234 mm. The third and final pilot study was conducted to develop a delivery system that could be used interchangeably with the existing inkless shoeprint kit. For this, different types of materials were investigated to identify suitable materials for designing the control sampling pad. The outcome of this study identified the chamois leather as the most appropriate material for the control sampling pad

because of its texture and composition. Following this, a control sampling pad was designed by stitching the chamois leather into a non-porous sleeve.

The following chapter of this thesis will conduct an empirical study to investigate the different methods that are used to gather control bare footprints. This study will examine the results obtained from surveys that were completed by forensic podiatrists and other bare footprints researchers to identify the most common approach for gathering control bare footprints. This study will ensure that the final method for recording control samples with the lotion and chamois pad (lotion system) can be adopted as an alternative to the inkless shoeprints kit (inkless system) and conforms to the methods suggested and recommended by the forensic podiatry community (DiMaggio and Vernon 2017; Burrow 2015; Reel 2012).

CHAPTER 3: Survey of bare-footprint sampling approaches

3.1 Recording Control bare footprints

Control bare footprints, also known as exemplar prints are bare footprints (latent or patent) collected from a suspect on request by the police or forensic examiners (DiMaggio and Vernon 2011; Ulery et al. 2011). The term 'control prints' also includes any known impression retrieved from individuals for use in research or data collections. Both static and dynamic exemplars are commonly retrieved, where the foot is at a standstill or walking respectively (Reel et al. 2010; Reel et al. 2012a). In addition to these, it may be necessary to take further exemplar prints that mimic the condition(s) of the questioned prints when they were first discovered at the crime scene. For example, this might include running impressions, if this is indicated as possibly being a contributing factor to the formation of the print/mark (see Jira 2017 for techniques and methods of capturing questions bare footprints, marks or impressions from crime scenes). DiMaggio and Vernon (2011) indicates that to deem any exemplars fit for use in casework, the exemplar prints should be collected in a controlled environment. However, creating a controlled environment can be problematic for obtaining bare-footprint exemplars due to the number of variables involved when an individual deposit a bare-footprint. For example, the creation and recreation of dynamic bare footprints is particularly problematic due to the interactions of the intrinsic and extrinsic muscles or the variability seen in different individuals gait (Reel et al. 2010; McPoil et al. 1999; D'Août and Aerts 2008). These variables not only include overall foot position but also the weight bearing area both longitudinally and laterally along the foot, toe position and the force applied. These variables should be in their 'natural' state when recording bare footprints so as to mimic the normal use of the foot (Reel 2012). In addition, the composition and flatness of the surface upon which the footprint is placed will also influence the subsequent impression made and this should also be considered when taking control prints.

The reasons for taking control bare footprints and the fundamental philosophies behind how practitioners retrieve them are similar to other impression evidence such as fingerprints, footwear, tire, lip and ear prints (Ulery et al. 2011; Bodziak 2017). Control prints allow the examiner to compare unknown marks to known marks and input them into appropriate databases such as the Automated Fingerprint Identification System (AFIS) or Treadmate (AlGarni and Hamiane 2008; Levitt 2007; Hannigan et al. 2006; Rajiv and Weicheng 1994; Lux 2013). Currently, there is no bare-footprint database which is dedicated to datasets

acquired from specific racial groups, which is accessible to academic researchers and forensic podiatrists. For example, to answer specific research and criminal casework questions. The need for such a resource has been expressed in the forensic podiatry community (DiMaggio and Vernon 2011; 2017). Unlike bare footprints, exemplar fingerprints act as a record of a person's identity and may be used to help identify an individual, whereas bare-footprint, marks or impressions will depend on their state of preservation. In most cases, bare footprints are used as corroborative evidence, to support other forms of evidence unless, exclusive individual characteristics are clearly exhibited and match with the known bare-footprint, mark or impression. Bare footprints analysis relies on the comparison of both qualitative (outline, presents of all characteristics e.g. creases, phalange marks, arch) and quantitative (linear measurements of the footprint dimensions) characteristics and provides, at best, the probability of the combined characteristics seen in an unknown mark, print or impression being from a particular individual (Hammer et al. 2012b; DiMaggio and Vernon 2011). Therefore, to provide such knowledge of the prevalence of certain characteristics in distinct races, large datasets of bare footprints are required using an appropriate comparable method and materials. Collecting large datasets of bare footprints and developing a database of exemplars can provide this information, but would require a standardised approach to ensure that the exemplars have been created in a consistent manner which does not affect the key characteristics.

On the other hand, fingerprint exemplars require an exact representation of the friction ridge details, whereas, in forensic podiatry, a good clear foot outline that accurately represents the natural weight-bearing area of the donor is enough (DiMaggio and Vernon 2017; Kennedy and Yamashita 2007). In this sense, considerations for taking control prints must consider both the overall footprint morphology and ridge detail. In addition, it is important that the bare footprints intended to be gathered as exemplar prints for a reference database should be recorded using a consistent and reliable approach. Currently, there is a method and guide which was designed by Reel (2012) for sampling two-dimensional static and dynamic bare footprints prints which is highly recommended by the forensic podiatry community as best practice. However, although this guide is regarded as good practice for recording static and dynamic prints, the information is lacking details relating to what constitutes a good quality two dimensional bare footprints. Furthermore, it is suggested by Reel (2012) that following this guide to the letter, this will allow the operator/collector to capture the barefoot under sole in its natural state. In addition, there are no studies conducted to assess how this guide is interpreted by collectors using it. The information in the guide is limited and the researcher can only assume that

following the instructions will produce quantifiable exemplar prints, whether it was followed poorly or proficiently. In this study, it was important to set out a definition of good quality, medium quality, and poor quality bare footprints, For example, a good quality bare-footprint exhibits a clear morphological outline, clear ridge details, all or most of the toes with phalanx marks as reflected by the weight bearing area and any crease marks that are apparent; followed by medium quality which might exhibit less defined foot outline, some ghosting marks and partial ridge detail; and poor quality denotes to an inconclusive bare-footprint or mark (Figure 3.1).

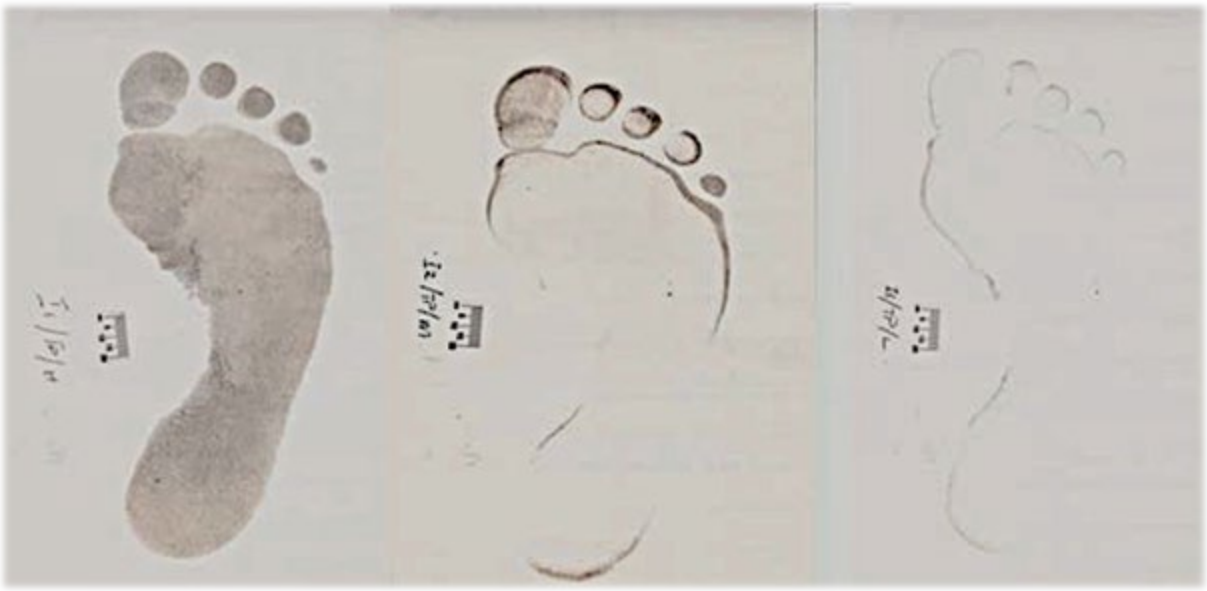

Figure 3. 1: Illustration of the 3 static footprint qualities: (i) High, (ii) Medium and (iii) Low quality

However, the ridge detail can depend on the donor's weight, for example, the more weight the more smudged the bare footprint with little to no details of the friction ridge marks (observed during pilot studies). Particularly this information is vital when attempting to distinguish between good quality, medium quality, and poor quality. The available literature indicates a a number of sample collection techniques, which suggests a standardised approach, these are the methods by Reel (2012), DiMaggio and Vernon (2011) and the podotrack by Burrow (2015). Therefore, the main aim of this chapter is to conduct a survey targeted at forensic podiatrists and bare footprints researchers to assess the different approaches to recording control samples.

3.2 Aims and objectives

The main aim of this aspect of the current research is to conduct an online survey targeting practitioners working in forensic podiatry and bare footprints researchers, to ask questions relating to the materials and procedures they utilise for control sampling bare footprints. The outcome on this study will aid the researcher when designing a control sampling method, which is parallel to the method subsequently identified as common approach by the respondents.

3.3 Method (Survey Design)

A simple, user friendly, online survey using Qualtrics was created containing 11 questions (see Table 3.1 for an overview of these questions).

Details of the Survey

Section A: Job Role Information

A 1. From the list of jobs below, please tick all that apply to your current employment?

a) Scene of Crime Officer (SOCO)
b) Clinical Podiatrist (CP)
c) Forensic Podiatrist (FP)
d) Forensic Gait Analyst (FGA)
e) Police Custody Officer (PCO)
f) Police Custody Nurse (PCN)
g) Other mixed roles

A 2. Are you required to seize and recover barefoot marks from crime scenes?

a) Yes
b) No

Section B: Collection & Verification of Exemplar Barefoot prints

B1. Does part of your job require you to collect exemplar barefoot prints (**exemplar barefoot prints refer to prints produced and collected on request from a known person under controlled conditions**)

a) Yes
b) No

B2. From the methods below, which of these is your preferred method of collecting exemplar barefoot prints?

a) Ink-less shoe print kit (Ink-less Reagent and Treated Paper)
b) Fingerprint Ink and a long roll of white or brown paper
c) Other; please list below your preferred method/s.

B3. Do you ever consider the time of day as a variable for the collection of barefoot print/s?

a) Always
b) Sometimes
c) Never

B4. If you have chosen **Always** or **Sometimes** to B3, why do you consider the time of day as a variable?

B5. In order to collect exemplar barefoot prints that best represents the natural barefoot of an individual, what is the ideal length in meters (m) of walkway would you use or recommend to other practitioners?

B6. When requested to collect exemplar barefoot prints, please choose from the list below the types of barefoot prints you would normally collect?

a) Static (standing)
b) Dynamic (Walking)
c) None
d) Other (Please specify)

B7. When collecting exemplar barefoot prints, what is the ideal number of dynamic (walking) and/or static (standing) repeats would you capture or recommend to other practitioners?

B8. If the participant or suspect is uncooperative, what actions would you take?

B9. After capturing exemplar barefoot prints, how would you **VERIFY** the barefoot print/s to be the true and best representation of the natural barefoot of an individual?

Table 3.1: Illustration of survey questionnaire

Section A focussed upon the role of the respondent and Section B contained questions regarding the collection of control prints from individuals. Questions were designed so that they gathered information about the participant's experience of recovering exemplar prints from individuals which then allowed them to expand on the methods they had previously used. The survey was designed so that participants could opt out of any questions at any time and any information gathered would be anonymous. There were no 'correct' answers; the survey's aim was to obtain information about different practitioners' experience in bare-footprint impression evidence to help develop a database that contains fit-for-purpose samples that could be used universally to aid interpretation. Prior to the implementation of the survey, full ethical approval was granted for this study by Staffordshire University's Ethics Committee (see Appendix A.1).

3.3.1 Survey Implementation and Sample.

Online research was conducted to identify law enforcement agencies, academic institutions and organisations that mentioned podiatry on their websites. An email link of the survey questionnaire was sent to suitable participants. The email also contained some background information of why the survey was being conducted and information relating to the data collection process. The individuals targeted for the survey had all published within the area of forensic podiatry or bare-footprint related studies. The organisations targeted were known to have conducted some form of forensic examination of bare footprints. In total fifteen countries were invited to contribute to this survey. To distribute the survey, the online link was sent out via email to three UK Police forces and three international Police forces (Denmark, South Africa and Canada); three UK and four international forensic providers/organisations (two in the USA and two in South Africa that conduct either gait analysis or bare-footprint analysis; three UK Higher Education Institutes (HEI's) and eleven international HEI's (Austria, two in Australia, Croatia, three in India , Malaysia, Ghana, Tanzania and South Korea) who deliver courses and/or conduct research in forensic podiatry. The survey was also sent to seven UK and eighteen international individual forensic podiatrists, barefoot researchers and gait analysts (three participants in Australia, three participants in Canada, three participants Croatia, two participants India, one participant in South Africa, two participants in South Korea, one participant in Spain, one participant in Nigeria and two participants from the USA).

The information that was provided to organisations requested that the survey is directed to personnel with some experience of forensic podiatry, including those that have maybe been required to retrieve bare footprints from crime scenes, retrieve control samples from suspects or individuals for research and/or analyse the subsequent impressions either for casework or research. This allowed the survey to be directed to a greater number of potential participants which would be narrowed down by role and experience once they read the information provided with the survey. This information outlined the aims of the survey, the reasons for carrying it out, the question topics and what will happen to the data. Social media (LinkedIn and Twitter) was also used to target appropriate practitioners and make them aware of the survey to try and maximize the number of respondents.

3.4 Qualitative Data analysis

In this experiment, qualitative data was recorded from the participants who completed the e-questionnaires. This study examined the information within each response to assess if the outcome was influenced by country of origin, law enforcement, educational institution or by job role/profession. The results were also analysed using Microsoft Excel (version 15.32) to assess if the material and methods used (by each participating subject) to acquire control bare footprints had any influence in their response(s), or whether, accessibility to the materials and geographical location, were the influencing factors to their responses. The survey responses were summarised into tables.

3.5 Results

In total, 25 responses were obtained from nine different countries, followed by four responses from participants who did not want to disclose their geographical locations. The results presented in this study do not disclose specific information that may lead to the participants' identity. The results will only present the responses by country and summarise the results according to each survey response. Table 3.2 illustrates the geographical distribution of the participants and their declared job description/roles. Within the responses, some of the participants indicated that they only had one single job role, while other participants selected mixed or multiple roles. This meant that each respondent (even if they had selected multiple roles) was recorded as a single entry in Table 3.2.

Geographical Location of Participants	Number of Participants & Job Description				
	Single Role			Mixed Role	Other
	Scene of Crime Officer	Forensic Podiatrist	Clinical Podiatrist		
UK	Total = 1	Nil	Total = 4	Total = 5 Clinical & Forensic podiatrist and Researcher (x1) Forensic podiatrist and & Forensic Gait Analyst and Research Supervisor (x1) Detective inspector and Crime Scene Investigator (x1) Clinical & Forensic Podiatrist and Forensic Gait Analyst (x1) Clinical Podiatrists and Gait Researcher (x1)	Total = 4 Police Custody Officer (x1) Unspecified Role (x2) Bio-engineer (x1)
Canada	Nil	Nil	Nil	Nil	Total = 1 Forensic Identification Specialist (x1)
USA	Nil	Total = 1	Nil	Total = 3 Forensic Podiatrist & Clinical Podiatrist (x3)	Nil
Mauritius	Nil	Nil	Nil	Total = 1 Forensic Scientist (x1)	Nil
South Africa	Total = 1	Nil	Total =1	Nil	Nil
Nigeria	Nil	Nil	Nil	Total = 1 Researcher in forensic science (x1)	Nil
India	Nil	Nil	Nil	Nil	Total = 1 Lecturer and researcher (x1)
Australia	Nil	Total = 1	Nil	Nil	Nil
Denmark	Nil	Nil	Nil	Total = 1 Detective Inspector & Forensic Investigator (x1)	Nil
Croatia Malaysia Austria South Korea Ghana Spain	Nil	Nil	Nil	Nil	Nil
Unknown	Total = 1	Total = 1	Total = 2	Nil	Nil

Table 3.2: Geographical distribution and declared job descriptions/roles of participants

It should also be noted that the number of participants who attempted the online questionnaire is not equal to the number that completed both sections of the survey. Some of the participants started to respond to the questions, then dropped out before completing the survey. Skip logic on the questionnaire was enabled on questions A1 and B2, and respondents to be directed to certain questions according to their responses. This process ensured that responses were collected from the relevant subjects of interest (participants who dealt with bare footprints). The responses from A2 and B2 combined, indicated 6 of the participants were required to recover from crime scene, 10 required by their job role to record exemplar prints from the suspect. Following this question, the participants were asked to indicate their preferred method(s) and materials for collecting exemplar bare footprints. The participants were

provided with three options to choose from, for example, there were provided with a list of common materials used for sampling bare footprints. Figure 3.2 shows the responses to question B2. If their preferred materials were not listed, the participants were asked to provide more details in the space provided on question B2. From the two participants who typed their methods, one indicated "Podotracks" and the other participants indicated "Copy-foam" (for comparing to three-dimensional impressions).

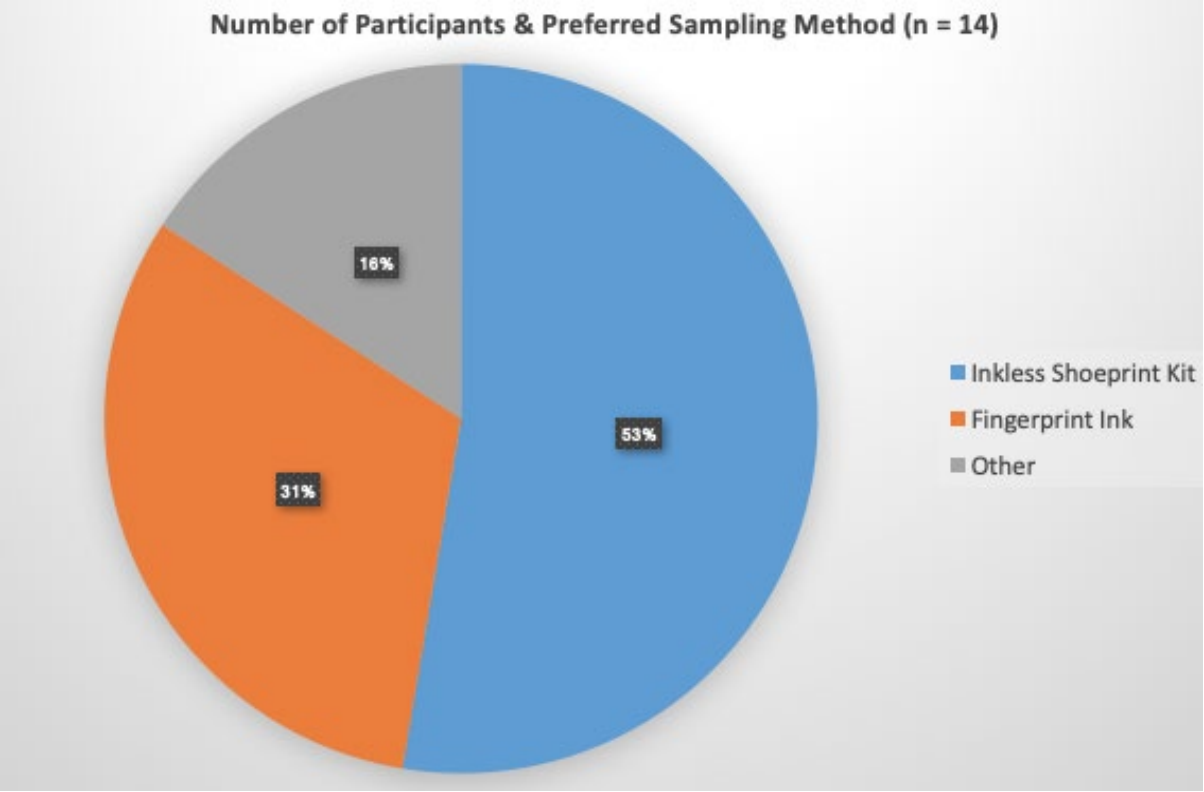

Figure 3. 2: Indicating the number of participants and their preferred method(s) for collecting exemplar bare footprints (n =14)

The participants were also asked to indicate if they regarded the time of day as variable (diurnal variation was a factor to consider before collecting control bare footprints (Table 3.3). 36% of the participants answered 'always' and 36% answered 'sometimes' (10 participants). The other 29% (four participants) indicated that, they did not consider the time of day as important to the outcome of the bare footprints. The participants were prompted to elaborate and seven of the participants responded. The participants indicated that diurnal variation in the foot volume was the main reason they regarded the time of day as a variable.

Geographic Location	Job Role(s)	Response	Comments
Australia	Forensic Podiatrist	Always	To control for diurnal variation in foot volume.
Denmark	Detective Inspector, Forensic Investigator	Always	
United Kingdom x3	Clinical & Forensic Podiatrist and Gait Analyst	Always/Sometimes	
USA x2	Clinical & Forensic Podiatrist	Always	

Table 3.3: Illustrating the summary of the response from the survey extracts (n = 7)

Geographical Location	*Job Roll(s)*	*Length of walkway*	*Number of Exemplar Prints*	*Sampling Protocol*
Australia	Forensic Podiatrist	Enough for 4 - 6 step protocol	3 from each foot, Static & Dynamic	Yes
Canada	Forensic Identification Specialist	10 - 12 meters	5 dynamic & 4 - 6 from each foot static	None
Denmark	Detective Inspector, Forensic Investigator	5 meters	10 dynamic & 4 from each foot static	Yes
Nigeria	Forensic Scientist, Researcher	Not disclosed	3 - 4 from each foot	None
United Kingdom	Clinical, Forensic Podiatrist & Gait Analyst	Enough for mid-gait 3 - 4 step protocol	2 static & 2 dynamic from both feet	Yes
United Kingdom	Clinical Podiatrist, Gait Researcher	None disclosed	5 static & 5 dynamic from both feet	None
United Kingdom	Clinical & Forensic Podiatrist, Researcher	5 meters for mid-gait protocol	3 from each foot, Static & Dynamic	Yes
United Kingdom	Forensic Podiatrist & Gait Analyst	8 - 10 meters	3 from each foot, Static & Dynamic	Yes
United Kingdom	Researcher	None disclosed	6 from each foot	None
USA	Clinical & Forensic Podiatrist	6 meters	3 - 4 from each foot	None
USA	Clinical & Forensic Podiatrist	4 - 6 meters	3 - 4 from each foot	None
USA	Clinical & Forensic Podiatrist	5 meters	10 from each foot, Static & Dynamic	None

Table 3.4: Summary of the survey responses which indicates the geographic origin of response, job role, length of appropriate walkway for data collection, number of appropriate repeats and if a sampling protocol is used

The participants were further asked about their preference of walkway length, that would be appropriate for recording optimum quality dynamic and static bare footprints, or indicate their recommendations to fellow practitioners or researchers. The questionnaire also prompted participants to indicate the appropriate number of bare footprints they would usually capture and whether they would collect controls from both feet. The participants were also asked to indicate if they utilised a specific protocol when collecting exemplar prints. The results are summarised in Table 3.4.

3.6 Discussion

The advantage of data collection using electronic questionnaires (e-questionnaires), allows data to be collected on a national and international level and results in a greater number of responses. For example, the study can reach a larger population, when compared to traditional methods such as post and telephone research (Stewart 2003). This mode of data gathering is well received by researchers as an efficient and effective method of dispensing surveys (Coomber 1997). For example, distributing the survey using Qualtrics is cost-effective in terms of the benefits acquired from the money spent (Costigan 1999). Qualtrics Survey software allows the researcher to design and tailor a questionnaire to allow the gathering of specific data required to solve or answer a specific question (Heen et al. 2014). The results acquired, can be used as a guide/framework to enable improvements where deficiency is seen to be present (Stewart 2003). However, there are also many disadvantages to data collection using surveys. For example, some participants might feel like the survey is too long to answer or they might not be sure of what to say, resulting in low responses rates (Stone 1993). This problem was observed in this study, for example, some participants failed to complete specific questions. The low response rate recorded in this study could be influenced by this area of research due to being new and still gaining acceptance in mainstream forensic science (DiMaggio and Vernon 2017). The results observed in this study could be attributed to the few individuals working in this niche area. The results from the survey responses could potentially be biased due to the availability of materials or accessibility to the survey. Thus, it is not clear whether the true population of academic researchers and bare footprints researchers were sampled.

It is evident from these results that the sampling of bare footprints from suspects and recovery from the crime scene is not always conducted by the same individual(s). This survey was not able to acquire responses from scenes of crime officers (SOCO) as this survey was targeted at forensic podiatrists and academic researchers but some SOCOs did complete the survey (n = 3). The results question A2 and B1 (Table 3.1), indicate that only six participants had job roles that allowed them to recover bare footprints from both crime scene and suspects. Furthermore, the results indicated that the participants were from a mixed roles background like forensic identification specialists, scene of crime officer, forensic gait analysts and university researchers. When the participants were asked about the methods and materials, ten participants (53%) answered that they had used the inkless shoe print kit more than other materials (Figure 3.3). This result could be biased because most of the participants who answered this question are from the United Kingdom where the inkless shoeprint kit is recommended for research and

criminal casework. When asked to indicate if the participants considered the time of day as a variable to collecting bare footprints, there was an agreement between five of the participants who indicated that diurnal variation was always considered when recording bare footprints but did not elaborate. However, one participant indicated that they sometimes considered the time of day before recording bare footprints but this was not important. It is not clear if this response was influenced by a study conducted by Burrow (2015) about diurnal variation influenced by the time of day. The outcome of the study conducted by Burrow (2015) indicated that time of day did not affect the footprint measurement. However, it is clear from the sample size that this study was small (n = 16). In addition, there is no evidence from this study what the power of the sample size is or the effect size of the of the statistical outcome. According to Maher et al. (2013) and Lakens (2013), effect sizes are the most important outcome of empirical studies. It is important to know whether the experiment has an effect and if so, how much of an effect. Failure to report the measures of effect size contributes to omitting the robust part of the analysis. In addition, there is a greater chance of a type II error, for example concluding that diurnal variation is not a factor in bare footprints formation when it is important. In addition to this, the study conducted by Burrow (2015) failed to acknowledge other related studies conducted by Menz et al. (2014) and Houston et al. (2006) which clearly state that the volume of foot can potentially increase during the course of the day due to dimensional changes that are associated with gait and foot loading. This is also reported by Kouchi et al. (2009), that the fleshed foot volume changes between dynamic and static phases can increase by 1.4% after standing erect and walking for at least ten minutes. The study conducted by Burrow (2015) does not mention this. Thus, it would be beneficial for a comprehensive follow-up study to be conducted to investigate if there would be a different outcome to this current investigation. It is evident from the responses that most of the participants who chose to answer this question are from a clinical background (n = 7), indicating their knowledge of the foot and ankle physiology. These results also confirm that clinical podiatrists are more likely to be aware of diurnal variation when compared to other professionals (Table 3.3).

There were slight differences between the geographical locations with regards to the length of the walkway, the appropriate number of exemplar prints and if they utilised sampling protocols to ensure the collection of optimum bare footprints. When the participants were asked to indicate their favoured walkway length, participants from the USA indicated that they preferred using walkways that ranged between 4 to 6 meters (average mean length = 5.33 m). The participant from Denmark also indicated 5 meters, as suitable for recording optimum bare

footprints. The United Kingdom participants who commented indicated that they preferred walkway lengths between the range of 5 to 10 meters (average mean length = 6.33 m). Furthermore, the participant from Australia indicated a preference of 5.0 meters. Canada was the only location with the longest walkway length between 10 to 12 meters. These results seem to generally agree but some responses from Canada suggest a greater walkway length. It is evident from these results that there is some form of methodical approach which indirectly encompasses a 3 to 4 meter mid-gait process, suitable for capturing dynamic bare footprints (Burrow 2015; 2016). The length of walkways that were reported by the respondents was similar except for two responses (Canada and the United Kingdom) which suggested walkways ranging between eight to twelve meters (please see Table 3.4).

When the participants were asked to indicate whether they used a sampling protocol for collecting exemplar prints, there was a mixed response (Table 3.4). Although some participants indicated that they did not use a sampling protocol, all the walkway lengths preferences do facilitate some form of collection protocol. All the participant's preferences (walkway length), reflect measurements which would be recommended in a sampling protocol, albeit no formal protocol is currently followed during collection for these individuals. There were also differences in the number of exemplar samples that would normally be taken. Participants from the UK indicated a minimum of two static and two dynamic prints from each foot and a maximum of five static and five dynamic. Some of the participants did not specify if they collected both static and dynamic bare footprints, for example, participants from the USA did not specify the preferred number of each type of bare footprints, instead, they indicated a minimum of three and maximum of ten. There were also differences in the numbers of exemplar prints illustrated by the remaining participants (Australia, Canada, Denmark, and Nigeria), indicating the use of random approaches to collecting bare footprints. Table 3.4 contains a summary of responses from participants from each geographical location and their preferred sample quantity. The overall results of this study indicate a need for a more integrated approach that encompasses all the collection methods and allows for a standard approach to be utilised. The results of this study enabled this investigation to develop a sampling protocol for the lotion. Therefore, developing a control sampling protocol for the lotion will allow for a coordinated control sampling approach and consistency in the data gathered. In addition, lotion sampling protocol will encompass the key requirements highlighted by this survey and include elements suggested by the forensic podiatry community. The results of this study will ensure

that the proposed method will not fall far from the general norm observed in these results and the forensic podiatry community.

3.7 Conclusion

The overall aim of this chapter was to conduct a survey of the methods and materials regularly employed by forensic podiatrists, forensic practitioners, and bare footprints researchers to capture control bare footprints. Although the survey was sent to many organisations, only a few managed to respond. For the participants who managed to respond, there seems to be some agreement regarding what constitutes an ideal length of the walkway. In addition to this, the inkless shoeprint kit was the most preferred by both practitioners and researchers. The participants who responded to this study indicated some inconsequential differences in certain areas such as the collection of exemplar prints, which materials they used and their considerations before collecting bare footprints. However, there were some areas that participants illustrated a common approach, for instance, the walkway length for capturing dynamic bare footprints. The responses suggested that the walkway lengths were all adequate to capture good quality samples, similar to the walkway lengths recommended by DiMaggio and Vernon (2011). Nonetheless, there was a lack of consistency in the number of control exemplar recorded between the participants. These findings will provide a platform for developing a strict guide for sampling control bare footprints with the lotion. Most importantly, these results will aid this investigation in developing a method that is equivalent to the best practice reported in forensic podiatry published and the general methods suggested by the forensic podiatry community.

The following chapter (4) is a comparative study between the lotion and the inkless system. This chapter (3) investigates the lotion and the sampling pad developed in chapter 2 (pilot studies) using participants. The investigation conducted a comparative study of the lotion and the inkless shoeprint kit to assess if the lotion if comparable and can be adopted as a cheaper alternative, suitable for gathering large datasets of bare footprints.

CHAPTER 4: Evaluating the lotion: A comparative study between the bare footprints lotion system and the inkless shoeprints kit

4.1 Introduction

The research conducted to date shows that there are many methods and various materials which have been used to capture control bare footprints. For example, some of the materials that have been used in Canada include red paint and black fingerprint ink (Yamashita 2010; Hammer et al. 2012). In the United Kingdom, materials that are used include the podotrack and the inkless shoeprint kits, which are regarded as fit for purpose for criminal casework or for research purposes to capture two-dimensional dynamic and static bare footprints (Burrow 2015; Gordon Burrow 2016; Reel et al. 2012b). In addition to methods used in the UK, the inkless system is the most favored by forensic podiatrists and bare footprints researchers (Chapter 3, Figure 3.2). However, some of the most influential research in forensic bare footprints analysis reported using black fingerprint ink (Krishan et al. 2012; Kanchan et al. 2014; Krishan and Kanchan 2013; Krishan 2007; Qamra 1980). In other countries where the inkless shoeprint kit is not easily available, the fingerprints ink is mostly used because of its unquestionable integrity and ability to capture the true contact area when applied on friction ridge skin (Fieldhouse 2009). However, even though the participants in chapter 3 were given the opportunity to add comments about their most preferred method and why, none of the respondents provided further information. Judging from their responses, it can be concluded that the inkless shoeprint kit was the most preferred options because it is clean and easy to use and does not dissuade participants. Furthermore, it is also not clear whether these respondents were aware of the chemical composition of the inkless shoeprint kit or whether it is safe on human tissue. Because none of the respondents provided any additional information relating to the materials. However, the publications by Reel et al. (2010), Reel et al. (2012a) and DiMaggio and Vernon (2011) seem to suggest that the inkless reagent ink is not harmful or does not stain the skin, but this is not true. According to Fisher and Scientific (2013), the inkless shoeprint kit contains chemical properties that are hazardous to the human body. In addition, the user instructions for the inkless system emphasises that gloves and goggles should be worn all the time when handling the inkless shoeprint kit (CSI Equipment 2018). The major ingredient in the inkless shoeprint kit is 'ferric chloride' which has potential health effects that include irritation to the skin, irritation to the eyes or if ingested may cause blood, liver, kidney or nervous system

damage. Furthermore, the inkless ink can cause temporary staining to the friction ridge skin if adequate steps are not taken to clean the feet thoroughly after use. It is indicated by the LabChem (2017), that ferric chloride is highly corrosive to most metals and corrosive to tissue. It is also indicated by Fisher and Scientific (2013) that the inkless shoeprint kit was meant to be used for recording shoeprints, hence the name. However, its practicability to the sampling of bare footprints meant that researchers and forensic podiatrists disregard the health hazards and have adapted this system to suite bare footprints sample capture. To date, there are no follow-up studies that are published or indication that there are studies planned to investigate if there are any long-term side-effects caused by the ferric chloride from the inkless shoeprint kit. An investigation by Burrow (2015), reported conducting a comparative study between the inkless system and the podotracks but, failed to provide sufficient information relating to any hazardous materials within the inkless shoeprint kit. Instead, there were a few details in the study which mentioned that the podotracks were messy, because of the carbon. According to Algeos (2018), the carbon on the podotrack can potential contamination the hands if protective personnel equipment is not used, but, the podotracks is safe and recommended by the National Health Service to podiatrists for identifying foot typology. The footprints sampling methods presented earlier in section 2.4 (e.g. fingerprint ink or the inkless shoeprint kit) are either messy, very costly or hazardous if used inappropriately. This chapter builds on the findings of derived from the pilot studies in chapter 2. Therefore, this chapter will investigate a new approach that utilises a lotion and chamois leather pad (lotion system) and compare this to the inkless shoeprint kit system.

4.2 Aims and objectives

The overall aim of the following experiment is to conduct a repeated measures comparative study between the lotion with chamois leather pads (bare footprints lotion system) and the inkless shoeprint kit, to assess if the bare footprints lotion system could be adopted. To archive this aim, this study will recruit 25 participants and record control bare footprints using both the bare footprints lotion system and the inkless shoeprint kit.

4.2.1 Research Question

1. Is the lotion suitable for bare-footprint sample collection, as an alternative to the inkless shoeprint kit?
2. Are the two sampling papers (treated and thermal) comparable to each other when used to sample two sets of the same data?

3. Is there a difference in the measurement technique or sampling technique between all groups?

4.2.2 Null Hypothesis

- There is no statistically significant difference between two sets of data collected using the lotion and the inkless shoeprint kit
- There is no statistically significant difference between thermal paper for the lotion, and treated paper for the inkless shoeprint kit

4.2.3 Alternative Hypothesis

- There is a statistically significant difference between two sets of data collected using the lotion and the inkless shoeprint kit
- There is a statistically significant difference between thermal paper for the lotion, and treated paper for the inkless shoeprint kit

4.3 Materials and Methods

Participant recruitment, Research Ethics, and Populations

Before participants could participate in this investigation, ethical approval was sought and granted by Staffordshire University Ethics Committee (see Appendix A.1 and A.2 for ethical approval and dates). The participants were recruited from Staffordshire University using the intranet system. The recruitment email contained information about the project and what would be required from the participants and informing the participants in advance that they would be required to provide biological data (height, weight, and age) and to remove their shoes so their bare footprints to be captured. The participants were also provided with two information sheets (i) for the inkless shoeprints system and (ii) for the bare footprints lotion system, both of which contained all the information regarding potential effects of using both materials. These information sheets also provided information regarding the rights to withdraw from the study and the potential risks of using the inkless system (please see Appendix B.1 and B.2 for the information sheets). Once the participant had consented to have their bare footprints recorded, they were asked to complete a self-assessment questionnaire to allow categorisation of their data. This data was captured electronically and stored in Qualtrics. The self-assessment questionnaire consisted of two blocks of questions, block 1 biological questions and block 2 for demographic questions. Table 4.1 illustrates the example of the questionnaire. The

participants recruited to take part in this study consisted only of students and academic staff members from Staffordshire University (Race = White British, age range = 20 to 64 years, mean age = 38.44 years; sex = 13 males and 12 females). The power of the sample size was calculated using G-power software. A sample size of 25 was deemed sufficient for this investigation. The justification of this sample size is presented in chapter 2 section 2.4.2.

BLOCK 1: BIOLOGICAL QUESTIONS
1. To enter the unique reference number (please see Table 7.1 for illustration of the cording method utilised to assign an individual UNR to each participant)
2. Any foot disorder(s)?
3. Age (to be eligible to the data collection, the participant should be above the age of 18) I. Gender II. Height III. Weight IV. Foot dimensions using Brannock device
END OF BIOLOGICAL QUESTIONS
BLOCK 2: DEMPGRAPHIC QUESTIONS
1. White, White British a) Irish b) Welsh c) English d) Scottish e) Other White Background _____
2. Asian, Asian British a) Indian b) Pakistani c) Bangladeshi d) Chinese e) Korean f) Sri Lankan g) Other Asian Background _____
3. Black, Black British a) Caribbean b) North African c) East African d) West African e) Central African f) South African g) Other Black Background _____
4. Fiji, Fijian British a) Melanesian b) Polynesian c) Other Fijian Background
5. Mixed Heritage, British a) White and Asian b) White and Black Caribbean c) White and Black African d) Other White Background _____
END OF DEMOGRAPHY QUESTIONS

Table 4. 1: Illustration of the Qualtrics questionnaire utilised to acquire the biological and demographic data.

4.3.1 Control Sampling Method: The Inkless shoeprint kit System

The inkless shoeprint kit (product code: 95818) and treated papers (product code: 95819) were purchased from CSI Equipment Ltd (UK). For this study, one inkless system (pad) and three hundred inkless system treated papers were used to acquire the control bare footprints. To ensure that the control bare footprints were standardised, the method developed by Reel (2012) was adopted to record the data. Full details of this method can be found in a control sampling manual developed by Reel (2012). A spacious area with a minimum 5-meter walkway and a non-porous hard floor surface (e.g. laminate, linoleum, wood, and other hard tiles) was used. Masking tape was used to mark the 5-meter walkway (tape width 2.5 cm) and the adjacent wall (1.5 meters from the floor). Each participant's height was recorded in centimeters, using a Marsden standard height scale (measuring ranges from 0 cm to 200 cm: with graduations of 1 mm). The weight of each participant was also measured using a laboratory standard weight scale (measuring capacity of 182 kg). The Brannock device was used to measure the arch type and overall shoe size. Each participant was instructed to remove their footwear and walk back and forth, along with a designated 5-meter walkway for two minutes, one at a time. After 2 minutes, the participants were provided with a series of instructions. Participants were asked to (a) stand comfortably with both hands on their side, (b) position their feet on either side of the inkless pad and (c) evenly distribute their weight (to allow the capture of a well-defined weight bearing area). Participants were also asked to stand erect with their eyes fixed on a marker on the adjacent wall during the deposition process. Subsequently, the participant was asked to (i) raise their right/left (depend on which foot is being recorded) foot and place it onto the inkless pad, (ii raise the foot and place it on inkless system treated paper and finally (iii), lift the foot and place it back on its original position.

4.3.2 The Bare footprints Lotion System.

The bare footprints lotion was dispensed from a 500ml pump bottle. A total of 300 pieces of (pre-cut, measuring 45cm x 25cm each) thermal paper were used to capture control static bare footprints. For the sampling pad, chamois leather measuring Length = 40 – 42 cm x Width = 20 – 22 cm, stitched to non-porous sleeve to prevent unnecessary movement during sample collection (Chapter 2; Figure 2.13). Before the control bare footprints were recorded using the bare footprints system, the chamois pad was first pre-loaded with 15 ml of lotion, evenly spread on all surfaces of the chamois leather using a wooden spill stick (Figure 4.1). The chamois-pad was placed in suitable sized plastic bag and left for 10 minutes to allow the lotion to moisten

the chamois leather. This was followed by pre-loading the roller brush with 10 ml of the lotion before evenly spreading the lotion all over the chamois-pad. The roller brush was used using an up – down motion until the pad surface was evenly covered with the lotion. Figure 4.2 illustrates the type of roller brush used for the distribution. To set the sample recording paper, the thermo-chromic paper was placed on a non-porous floor substrate, side-by-side to the pre-loaded chamois pad. To capture the samples, the same criteria for the room and instructions to participants as those suggested by Reel (2012) for the inkless shoeprint kit system was used for the bare footprints lotion system, however, for this method six repeats were recorded from each foot, as opposed to three repeats from one foot.

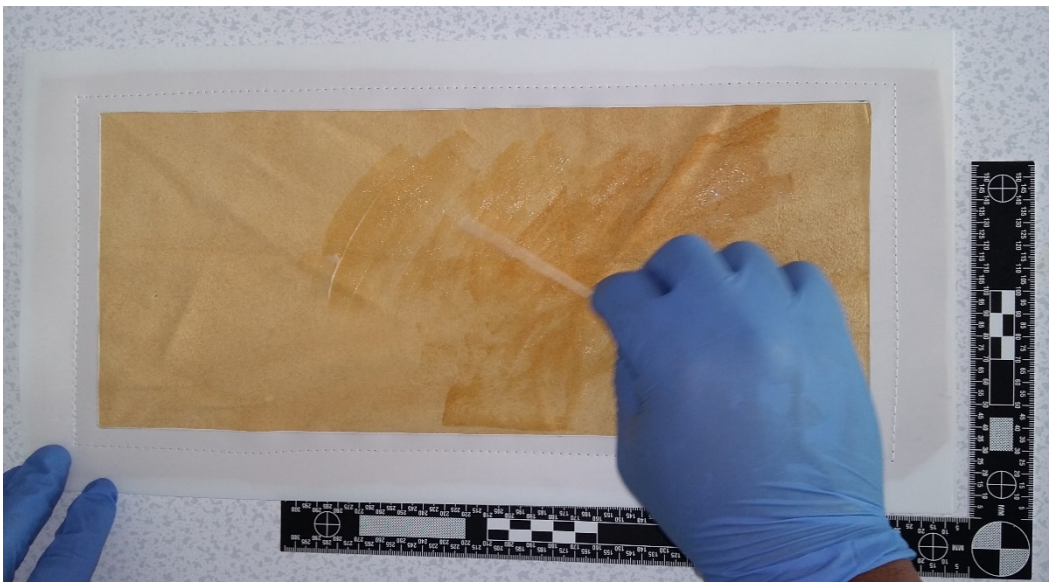

Figure 4. 1: The initial preloading of 15 ml of the 5 ml : 150 ml ratio on the chamois leather pad.

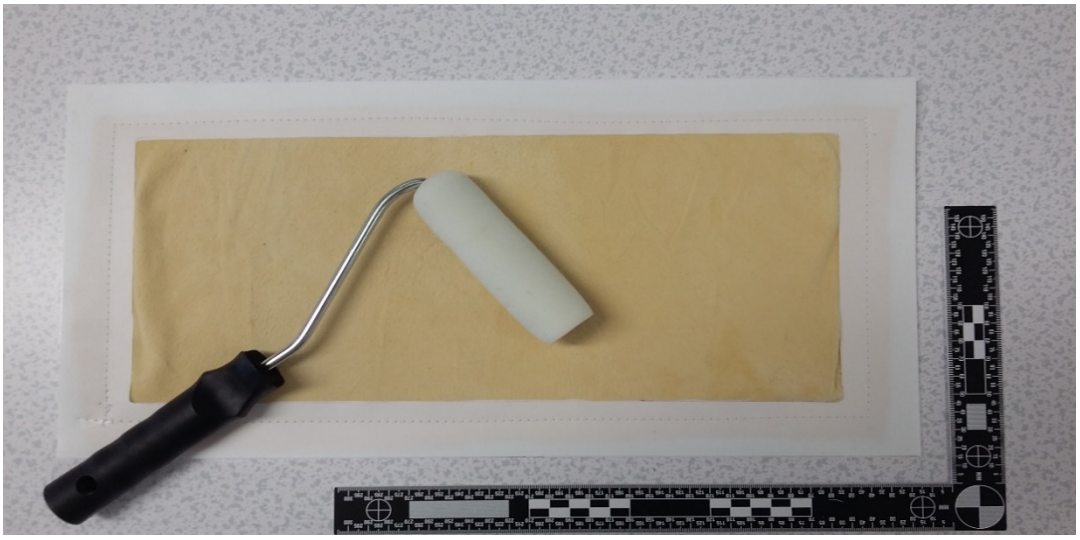

Figure 4. 2: Illustrating the type of roller brush used for the even distribution of the lotion

4.3.3 Digitising and Measuring the Control Samples

A computer equipped with an i5 intel processor and sufficient storage space to store the large data files was utilised. All the control bare footprints were digitised by scanning the hard samples using a flatbed scanner manufactured by Canon, model: Canoscan LiDE 110. The optical resolution was set to 300dpi and the image format set to capture Tag Image File Format images (TIFF format) to prevent image alterations. Adobe Photoshop CC version 2015.0.1 was used to acquire the quantitative data. Once the data processing was complete, the folders containing the images were appropriately labelled and uploaded to a storage device for further analysis. Each of the control bare footprints were subsequently measured in millimetres (mm) using Adobe Photoshop (version 2015.0.1.) The quantitative data from the bare footprints was derived from seven measurements of the foot, using the Reel (2012) method (Figure 2.11), previously mentioned in section 1.4.2 of this thesis. In order to facilitate reliable measuring, calibrations were performed to ensure the scale on the image and Adobe measuring scale were calibrated to measure at 1:1 measurement. The image processing method was selected in this study as it has also been used in research by DiMaggio and Vernon (2011). Thus, quantitative measurements were acquired using the below software settings and actions.

1. The image (which was saved in TIFF format) was opened in Adobe Photoshop CC 2015.
2. The layer function was used to flatten the image, to allow the placing of all layers together.
3. Using the function, View -> Grid, a grid was placed on the screen to allow the image to be aligned vertically to allow the calibration of the measuring rulers.
4. The line tool was selected and set to 0.1 and used to construct the lateral and medial tangents, the individual toe lines and the widths of the ball and heel.
5. To calibrate the measuring, the cursor was placed at the horizontal ruler (on the top of the screen) followed by using the right click option on the mouse to select ruler. The ruler was changed to measure in pixels to allow the scale in the image to be measured using the image scale.
6. The mouse pointer was set on the 0mm mark on the scale and measured to 20mm. This process provided with the measured length of the 20 mm pixels. The settings were implemented using the pixels acquired on the length 0 mm to 20 mm, to set as logical length 330 pixels = 20 mm.
7. The measuring procedure was followed by constructing and measuring each bare footprints using the Reel (2012) method (Figure 4.3).

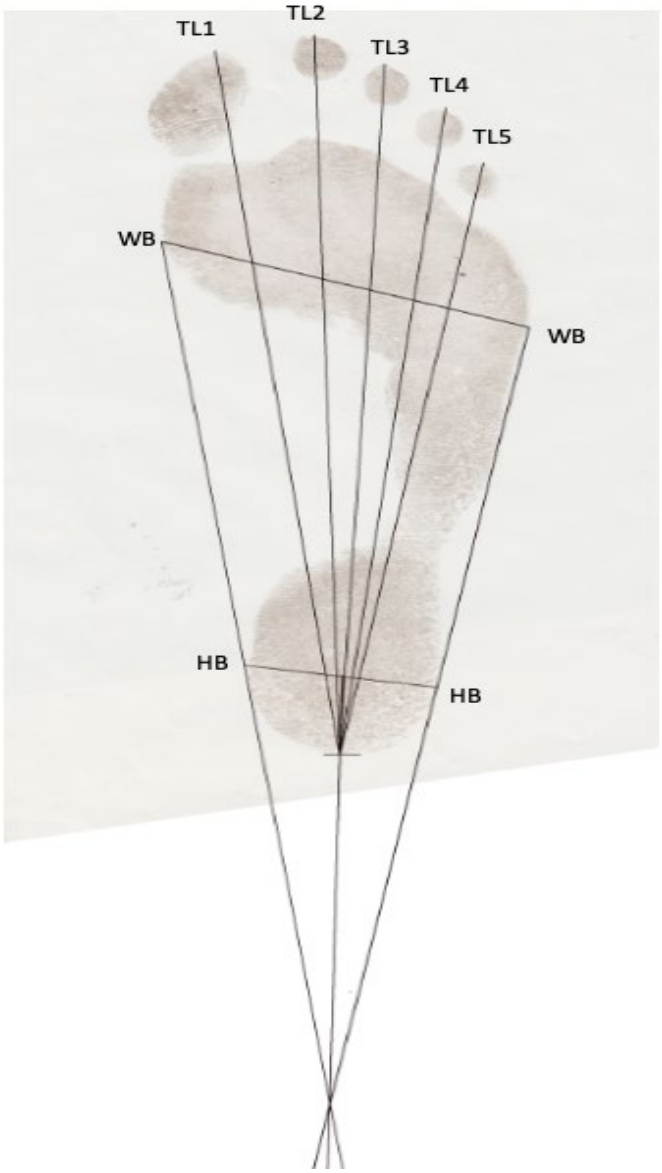

Figure 4. 3: Illustrating the method used to acquire the quantitative measurement data (Reel 2012).

4.4 Statistical analysis

The bare footprints sampled using the lotion system were first measured. This was followed by measuring the control samples captured using the inkless system. The measuring process involved recording the footprints lengths and widths. Five toe lengths and two widths of each footprint from the two groups of data using the Reel method (Figure 4.3). The measuring process resulted in the creation of two datasets: lotion and inkless measurements. It was noted that some of the data contained missing values caused by the toe(s) not contacting the recording sheet. According to Field (2013), data containing missing values for certain variables can be analysed, provided that the SPSS is informed that there are missing values. Hence, SPSS was coded to identify the missing values and to disregard the missing cases during the analysis. The data was explored using SPSS software version 23 to produce the descriptive statistics; mean, minimum, maximum, standard deviation, range and skewness. This also allowed for the distribution of data to be investigated thus to determine the appropriate statistical tests. It is indicated by Mccrum-gardner (2008) and Field (2009; 2013) that failure to assess the data for normality to determine the distribution can potentially lead to wrong statistical tests being applied. The assumptions of normality were assessed on both datasets (lotion group and inkless group) using the Shapiro-Wilk's test. The Q-Q plots and histograms were also used to visually inspect the distribution of the datasets, before it was determined that the paired *t*-test would be suitable to test if the two sets of data produced using the two experimental conditions (lotion and inkless) agree on average. According to Kim (2015), the paired samples t-test is used when two experimental data sets have been collected from the same object or participants. The paired samples *t*-test assesses both datasets to determine if there is a difference in the mean values. Effect size can also be calculated from the *t* statistic and degrees of freedom (*df*) (Field 2013). The size of the effect informs the researcher whether the effect is substantive, for example, the *t*-value is converted into an *r* value using the equation;

$$r = \sqrt{\frac{\mathrm{t}^2}{\mathrm{t}^2 + df}}$$

Equation 4 1: Effect size [r] equation

According to Maher et al. (2013) and Lakens (2013), effect sizes are the most important outcome of empirical studies. It is important for the researcher to know whether the experiment has an effect and if so, how much of an effect. The *r* effect size places emphasis on the

magnitude of the effect, as opposed to the *p*-value which combines both effect size and sample size into one result, thus providing a reliable outcome of the true measure of the variance (2002). According to Cohen (1992), the *r* effect size values can be interpreted as follows; *r* = .10: small; *r* = .30: medium; and *r* = .50: large). Thus, an *r* effect size is more reliable when assessing the efficacy of the proposed experimental condition. In addition to the paired samples *t*-test, the differences between the lotion and the inkless system were further investigated using the Bland-Altman plots (Bland and Altman 1986). This analytical method allowed the differences between the two groups of data to be investigated using 95% limits of agreement (LOA), For the Bland and Altman plots, the data was plotted in a scatter plot, where the X-axis measures the mean of the lotion and the inkless, and the Y-axis measures the difference between the two experimental conditions (Dolkar et al. 2013). According to Dolkar et al (2013), the Bland and Altman scatter plot is constructed with three lines. A line that denotes to the mean bias and two additional lines denoting to the upper and the lower limits of agreement set at 95%. Thus, 95% of the data would be expected to fall between -1.96 standard deviation (SD) and +1.96SD (Bland and Altman 1986; Dolkar et al 2013).

4.5 Results

Tests for the assumption of normality were conducted using the Shapiro-Wilk test. The results indicated that the two sets of data were all normally distributed ($p > .05$). The descriptive statistics for the data were calculated and are presented in Table 4.2.

Descriptive Statistics						
Substrate	Range	Minimum (mm)	Maximum (mm)	Mean (mm)		Std. Deviation (mm)
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic
TL1 Lotion	66.8	205.7	272.4	237.425	3.7566	18.7830
TL2 Lotion	57.5	209.3	266.8	237.752	3.5243	17.6214
TL3 Lotion	59.0	201.7	260.7	229.245	3.5481	17.7404
TL4 Lotion	57.3	192.0	249.3	217.228	3.4108	16.7095
TL5 Lotion	49.4	178.6	228.0	199.640	3.4116	15.6340
WB Lotion	22.5	78.4	100.8	92.529	1.2609	6.3044
HB Lotion	17.3	40.5	57.8	49.196	.9184	4.5921
TL1 Inkless	66.6	205.6	272.2	237.255	3.7527	18.7635
TL2 Inkless	56.2	209.7	265.8	237.539	3.4892	17.4458
TL3 Inkless	58.3	202.0	260.3	229.237	3.5399	17.6995
TL4 Inkless	57.3	191.9	249.2	217.206	3.4143	16.7264
TL5 Inkless	49.1	178.6	227.7	199.706	3.4048	15.6029
WB Inkless	22.1	78.2	100.3	92.192	1.2294	6.1471
HB inkless	17.7	40.9	58.6	49.153	.9304	4.6520

Table 4. 2: Descriptive statistics for the lotion and the inkless datasets, Lotion (n = 25), Inkless ink (n = 25)

The result from the paired *t*-test indicated that on average, there was no statistically significant difference between the two experimental conditions for all the toe lengths (TL1 -TL5) and the width of the Heel Ball (HB) ($p > .05$), except in the case of paired measurement of the width of ball (WB) which indicated a statistically significant difference ($p < .05$). The results for each paired measurement are as follows:

The paired lotion and the inkless TL1 datasets indicated that the two experimental conditions were comparable; lotion (mean (M) = 237.425, standard error of mean (SE = 3.76), inkless (M = 237.255, SE = 3.75), $t(24) = 1.67$, $p > .05$. The paired *t*-test results for TL2, indicated that there was no statistically significant difference between the two experimental conditions; lotion (M = 237.752, SE = 3.52), inkless (M = 237.539, SE = 3.48), $t(24) = 1.42$, $p > .05$. The results for the TL3 measurements paired, indicated that there was no statistically significant difference between the two experimental conditions; lotion (M = 229.245, SE = 3.54), inkless (M =229.237, SE = 3.53), $t(24) = 1.29$, $p > .05$. The results for the TL4 measurements paired,

indicated that there was no statistical significance difference between the two substrates; lotion (M = 217.228, SE = 3.41), inkless (M = 217.206, SE = 3.41), $t(23) = -.567$, $p > .05$, r = 12. The fifth paired measurement for the TL5, indicated that there was not statistically significant difference between the two experimental conditions, lotion (M = 199.640, SE = 3.41), Inkless (M = 199.702, SE = 3.40), $t(20) = -1.55$, $p > .05$. The paired results for the width of ball WB for both experimental conditions indicated that there was a statistically significant difference, lotion (M = 92.529, SE = 1.26), inkless (M = 92.192, SE = 1.22), $t(24) = 4.46$, $p < .05$. Finally the paired results for the width of the heel ball (HB) indicated that there was no statistically significant difference, lotion (M = 49.196, SE = .9184), inkless (M = 49.153, SE = .9304), $t(24) = 1.94$, $p > .05$. The resultant effect size (ES) calculated form the *t*-values for all the paired data ranged between $r = .12$ (small effect) to $r = .67$ (large effect). The experimental conditions also yielded a large correlation coefficient for all the pairs which ranged between r = .988 to r = 1.00 indicating a statistically significant correlation $p = .000$. The summary of statistical results are presented below in Table 4.3;

		Lotion System Measurement						
		TL1	**TL2**	**TL3**	**TL4**	**TL5**	**WB**	**HB**
Inkless System Measurement	**TL1**	✓						
	TL2		✓					
	TL3			✓				
	TL4				✓			
	TL5					✓		
	WB						×	
	HB							✓

Table 4. 3: Results indicating the comparative analysis of the lotion system and the inkless system, ✓ denotes to no statistically significant difference ($p > .05$), and × denotes to a statistical significant difference ($p < .05$).

The Bland-Altman plot, limit of agreement (LOA) set at 95% confidence interval (CI) were used to investigate the statistically significant difference observed between the WB measurements. The mean difference between the two datasets was plotted to visually inspect if there where outliers in the data (significant or insignificant) to conclude if there is comparability between the data sampled using the two materials. The results of the Bland-

Altman plot (Figure 4.4) indicated that there was only 1 data reading that fell outside the ± 1.96SD. This is insignificant, given that more that 95% of the data fell within the expected parameters. The results in Table 4.4 indicated that there was a very small difference of less than 0.5mm, if the ±5mm precedence set by forensic podiatrist is applied (DiMaggio and Vernon 2011).

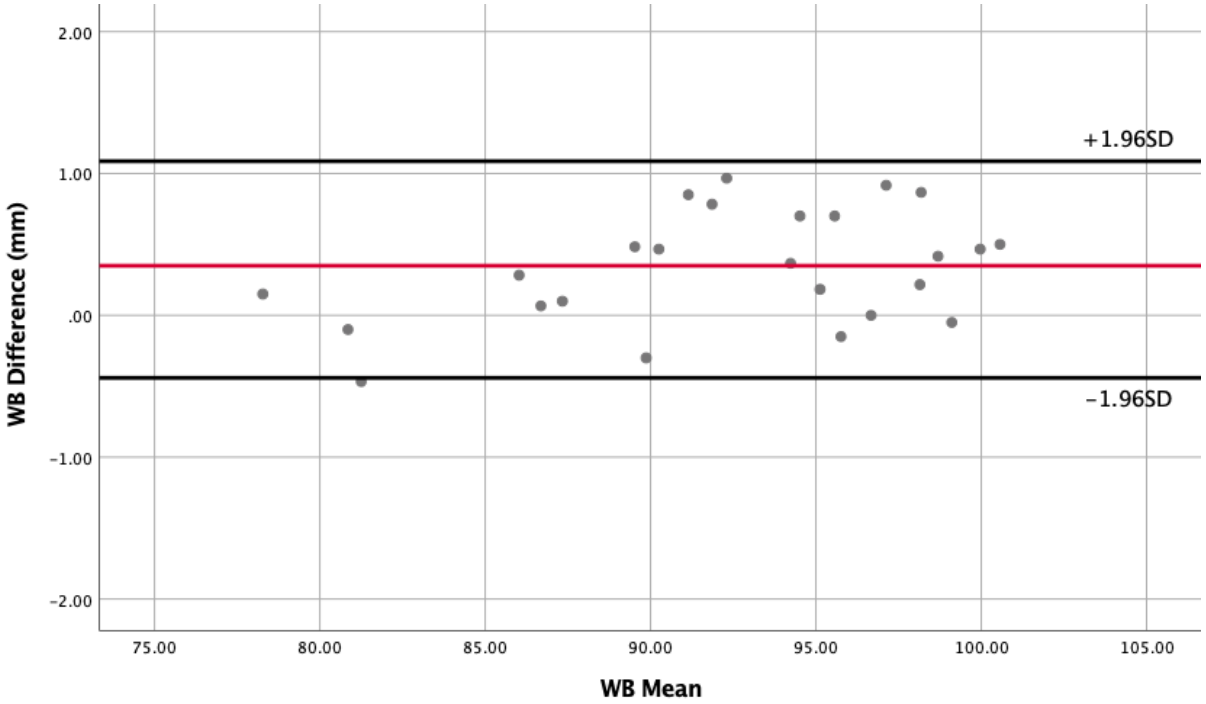

Figure 4. 4: LOA Lotion and the Inkless system, Right Foot Width of Forefoot Ball (WB), n = 25

4.6 Summary of key findings

The dimensions and overall qualitative results are supported by the statistical results which suggest there is comparability between the lotion system and inkless system. However, the statistical results also indicated that there was a statistically significant difference ($p < .05$) between the paired width of ball (WB) measurements. Further investigation of the paired WB measurement was conducted by plotting the mean difference of the two measurements using the Bland-Altman plot. This approach was adopted to determine if there was measurement agreement between the lotion and inkless systems. The results of the plotted data suggested that there was a very small difference, which is insignificant if we take into consideration that the mean difference is below 1 millimeter.

4.7 Discussion

Before a method can be adopted as an alternative, it is important to investigate the accuracy of that method. The main aim of this investigation was to assess if a cheaper and safer method to the existing sampling materials such as the inkless shoeprint kit, could be adopted as a viable alternative or identify if both methods could be utilised interchangeably.

For this study, a total 25 participants took part in this study and each individual had their bare footprints recorded with two different sampling techniques (lotion and inkless). Six repeat static footprints were recorded from each participant's right foot using each of the two sampling condition, resulting in 300 sets of footprints. The descriptive statistics indicated that the paired mean difference for all the measurements were not substantive therefore the two sampling methods are comparable. The two datasets (lotion and the inkless system) were further assessed using a paired samples *t*-test to investigate whether the null hypothesis could be retained, for example, if there was a statistically significant difference between the two sampling methods. The statistical results indicated that all (TL1, TL2, TL3, TL4, TL5, HB) but one (WB) were comparable. The results of the paired samples *t*-test suggested that the two sampling methods could be used interchangeably. This result is significant, given that the ingredients used to make the lotion are not harmful to the skin, as opposed to the inkless system which contains irritants (Fisher and Scientific 2013). Upon discovering that the WB measurement had indicated a statistically significant difference between the two sampling methods, a follow up investigation was conducted. This investigation identified from the descriptive results that the mean difference between the lotion and the inkless was small (mean difference = ± .337, SD = .4214) thus not substantive. Thus, it is clear from the results that the lotion method being tested here is comparable to the industry standard inkless shoeprint system.

The correlation results were produced as part of the paired *t*-test and these results indicated that the paired measurements were significantly correlated (p = .000). This result was expected, given that, the data was gathered from the same participants. Consequently, Giavarina (2015) suggests that the correlation should not be used to assess method comparability because it is misleading. Instead, the investigation should focus more on tests that examine the differences, and not the agreement between measurements (correlations). However, the measurement agreement was used to investigate the mean bias and to investigate if outliers were present in the data (Alsaedi 2018). For this, the Bland-Altman plots were constructed to determine the concordance between the lotion and the inkless datasets (Dolkar et al. 2013). These plots were

constructed to allow the research to evaluate the bias between the mean differences. The Bland-Altman plots, further confirmed that more than 95% of the data readings had fallen within 1.96 x standard deviation (SD) irrespective of the mean values at each measurement position. These results are substantive and sufficient to confidently conclude that the two sampling methods could be used interchangeably. This was evident on all Bland-Altman plots (Figure 4.4 – 4.10). Based on the results of this investigation, the 3 research questions set at the beginning of this study (section 4.2.1), the null hypothesis has been retained (1. There is no statistically significant difference between two sets of data collected using the lotion and the inkless shoeprint kit; 2. There is no statistically significant difference between thermal paper for the lotion, and treated paper for the inkless shoeprint kit).

The introduction of this chapter highlighted that the ingredients used to make the lotion was safe and cheaper when compared to the industry standard materials (inkless shoeprint system). The cost of producing the lotion is considerably low, for example, the inkless system which comes with 100 blank pressure-sensitive recording forms is sold at around £160 (CSI Equipment 2018). This study calculated the cost of the inkless shoeprint kit to £0.70 per sample (costing £8.40 for 12 control bare footprints: per individual); and the bare footprints lotion system £0.07 per sample (costing £0.84 for 12 control bare footprints: per individual). These costs are based on the current prices available on the market as of 2018/19. Thus, the lotion is cost-effective for generating large data sets. However, some of the limitations of using the lotion are that the chamois pad does not work instantly as the inkless shoeprint kit (Figure 4.1). The chamois leather pad requires to be loaded first with some lotion and placed in the nonporous plastic bag to allow the pad to moisten before it can be ready for control sampling. In addition, it is important that the correct quantity of the lotion is used to preload the pad, as overloading the chamois pad will result is distorted control bare footprints.

4.7 Conclusion.

This experiment tested the comparability of the data gathered using two bare footprints sampling methods. The statistical results indicated that the lotion system was reliable and thus could be used as an alternative method for sampling control bare footprints. However, even though there were small differences that led to a statistically significant difference between the lotion and inkless for the width of ball (WB) measurement. Further investigations were conducted and after examining the descriptive statistics and Bland-Altman plots, the difference

was not substantive. Thus, the null hypothesis was retained. In addition, this investigation also compared the cost of the of producing the lotion, which proved to be cheaper than purchasing the inkless shoeprint kit. Therefore, the lotion is more cost effective to generating large datasets required for conducting population studies.

Chapter (5) will investigate the reliability and comparability of data gathered by three individuals, an expert and two novice collectors. The control sampling will be conducted using the bare footprints lotion system to capture static bare footprints. The novice collectors will be provided with a control sampling manual to use as a guide.

CHAPTER 5: Reliability of the Bare footprints Lotion System: Post-hoc study

5.1 Introduction

The previous chapter demonstrated that the lotion system was comparable to the inkless shoeprint system, and both methods could be used interchangeably for sampling control bare footprints. Consequently, this investigation was conducted using bare footprints sampled by the author of his thesis only. Therefore, this chapter seeks to establish whether the lotion system is practicable, to be used by individuals with no experience of sampling control bare footprints. To do this, this chapter investigates the comparability and reliability of static bare footprints sampled using the lotion by three collectors, for example, an expert and two novice collectors. This chapter also investigates the usability of the sampling instructions provided to the novice collectors and their ability to sample static bare footprints that are of reasonably good quality (see section 3.1 for a definition of a good quality bare footprint). This current chapter will set out a benchmark for comparison using the control bare footprints sampled by the expert, and compare this to the bare footprints sampled by two novice collectors. The three sets of data will be sampled from the same participants. The results of this chapter will inform the overall investigation to establish whether the lotion system is practicable, captures data that is comparable and reliable.

To date, there are a few studies that have dedicated research of control sampling materials for two-dimensional bare footprints. This could be the nature of the area which is still in its developing stages. During literature research, only three publications were identified, one of which had partially investigated the control sampling materials. The first study examined the suitability of adopting thermo-chromic paper (fax) as an alternative to the treated paper supplied with the inkless shoeprint kit, to try and develop a cost-effective method for gathering large datasets of bare footprints (Heuser et al. 2012). In this investigation, a repeated measures experiment was conducted which involved the participants depositing static and dynamic bare footprints using two combinations of materials, (i) inkless ink shoeprint kit pad and the treated paper, and (ii) inkless ink shoeprint kit pad and fax paper. The notion underpinning this study was that numbers of footprints exceeding the 100 treated papers that came with the inkless pad could be produced. The study investigated if fax paper was the cheaper alternative paper and, if so, could it be adopted as an alternative to the treated paper. The second study was conducted

by Burrow (2015), who investigated the Reel method data acquisition technique on bare footprints obtained using the two different materials (the inkless shoeprint system and the podotracks). The outcome of this experiment concluded that there was a quality difference between the inkless shoeprint kit system and the podotracks. The outline of the bare footprints captured using the podotracks did not have a clear defined weight bearing area and it was difficult for the researcher to identify the exact position of the outline where the measurement should be taken from. In addition to this, Burrow (2015) also compared the Reel measurements acquired from bare footprints measured using two approaches, the manual method and the digital method, and concluded that there was no statistically significant difference between the two measuring approaches. This study is also supported by the investigation conducted by Nirenberg et al. (2019) of the Reel measurement acquired from two-dimensional dynamic bare footprint, measured using the manual method and two digital methods. However, even though these investigations conclude that there is no statistically significant difference between digital and manual methods, the bare footprints sampled from the fifty subjects investigated by Nirenberg et al. (2019), suggest that only one dynamic bare footprint from each foot was captured; a total of one hundred bare footprints were captured (two bare footprints per subject). DiMaggio and Vernon (2017), indicates that collecting dynamic bare footprints is particularly challenging, because certain protocols should be followed to enable the capture of optimum quality footprints that mimic the foot's natural weight bearing area. The protocol for capturing dynamic bare footprints includes using an uninterrupted straight walkway which allows for a four-step protocol, and positioning the sampling materials where the subject would most likely tread if they were walking in a natural way. However, this process introduces difficulties with the targeting during the data collection because the subject would require to target two materials (inkless system and the treated paper), and this can potentially introduce bias on the data (DiMaggio and Vernon., 2017). To date, there are no publications that have investigated if the targeting process influences the length or sizes of the ghost marks (please see section 1.3 where ghost marks are discussed further). Current research on bare footprints suggests that there are so many variables that influence dynamic bare footprints. Burrow, (2016) and DiMaggio and Vernon., (2017) highlight that there is potential bias introduced during the sampling process of dynamic bare footprints by the targeting process of the sampling materials (indicated above) as opposed to sampling static bare footprint. Consequently, the study conducted by Nirenberg et al (2019) sampled only one dynamic bare footprint per foot. This is insufficient to conclude that there are no differences between the three measuring approaches. Furthermore, the study conducted by Farrugia et al., (2012) suggests that a control measure

should be established to prevent introducing bias on the data. Static bare footprints are a reliable option and would have provided confidence in the outcome of the comparative experiment.

Reel et al (2010), investigated the inter-rater reliability (IRR) of bare footprint measurement technique. The IRR was part of a larger study that investigated the reliability of a two-dimensional measurement approach. For the IRR analysis, three operators were provided each with the same 30 randomly selected bare footprints and instructed by the researcher to measure the bare footprints using a set of instructions. The operators only measured the length lines from the random footprints using the Reel method (Figure 4.3) (Reel et al. 2010). Following this investigation, this study concluded that there was high reliability between the three operators, with standard error measurement (SEM) values ranging between 0.05mm to 0.07mm, with an interclass coefficient value of 0.99 for the comparisons between the operators. However, it is clear from this study that the subject of interest was the reliability of a measurement technique but, there was a missed opportunity to address a latent question relating to the instructions provided to the operators. Furthermore, only a specific set of measurements were reported which suggests that the results are narrow and limited. It is also not clear what criteria were used to randomly select the bare footprints for the operators and this information could have been beneficial to understand whether there was no bias in the sample selection process and the subsequent results. In addition, this investigation does not provide adequate information relating to the level of experience attributed to each operator. However, as useful as these studies may be, they do not answer the question if novice collectors or operators from different academic disciplines, with varying knowledge, or with no experience in bare footprints analysis are able to interpret the instructions to acquire good quality bare footprints using the bare footprints lotion system mentioned in chapter 4.

5.2 Aims

The overall aim of this chapter is to investigate the reliability of the quantitative data gathered by different individuals using the same set of instructions for the bare footprints lotion method listed in chapter 3. This study will enable the author to assess whether the instructions provided to the novice collectors were clear and effective enough to allow the novice collectors to interpret the instructions thus to acquire good quality bare footprints

5.2.1 Objectives

The objective of this investigation is to recruit two novice collectors and instruct them to independently collect control bare footprints from the same sample group of six volunteers using a set of instructions and the bare footprints lotion system. This will be followed by examining the data, to determine if the instructions for using the lotion system is practicable, and can be used by persons with no experience in bare footprint analysis.

5.2.2 Research Question

1. Is there comparability and repeatability between three sets of control bare footprints sampled by three operators (one expert and two novice collectors) using the lotion system?
2. Are the lotion system control sampling instructions clear to allow for reasonably good quality bare footprints to be captured by novice collectors?

5.2.3 Null Hypothesis

- There is no statistically significant difference between the three sets of data derived from the static bare footprints sampled by three operators (one expert and two novice collectors)

5.2.4 Alternative Hypothesis

- There is a statistically significant difference between the three sets of data derived from the static bare footprints sampled by three operators (one expert and two novice collectors)

5.3 Method

The sampling materials used for this study are also listed in section 4.3, chapter 4 of this thesis. For the bare footprint sampling process, the first set of bare footprints were collected by the expert separately then followed by two novice collectors, each collecting separately from the same sample of six volunteers, individually, and at different times. The volunteers consisted of two males and four females, their age ranging between 21 to 52 years old (males: age mean = 46 years, SD = 8.48 years; female: age mean =29.7 years, SD = 10.87 years). Each individual subject collected six static repeats (bare footprints) from the right foot, recording a total of six control bare footprints from each participant. Therefore, for the six participants, a total of 36

control bare footprints were recorded by each operator independently. The expert collector and the novice collectors all emanated from different backgrounds and with different levels of experience in bare footprints. For example, the expert was a postgraduate research student in Forensic Science; novice collector 1 was an undergraduate student in Biological Sciences and novice collector 2 was a college student undertaking the final year of A level's. The collectors were identified to possess different attributes (Kuntze et al. 2014), for example, novice collector 1 did not regard English as their native tongue and novice collector 2 was a visual learner (a learner who utilises graphs, charts, and images to construct knowledge / develop cognitive skills).

5.3.1 Sampling Environment

A designated area within the laboratory at Staffordshire University was used to for recording control bare footprints. This area of the laboratory was identified as suitable for capturing two-dimensional static bare footprints, based on the criterial set by Reel (2012). For example, the location had a hard floor surface that would allow the recording of two-dimensional bare footprints, further details can be found in Chapter 4 (section 4.3.1). Furthermore, this part of the laboratory would not restrict participants in terms of movement and would allow the participants to loosen up their lower foot before sampling commenced. The two novice collectors had no previous experience or knowledge of bare footprints analysis or the sampling process, so they were provided with a copy of the bare footprints sampling manual designed for using with the lotion system to use as a guide two days before the testing (Appendix D.1). They were also given the opportunity to ask questions, for example, if they were applying the lotion on the pad correctly and how they would know it was time to reload the pad with lotion during control sampling. Furthermore, the two novice collectors were also encouraged to practice control sampling during the initial two days to gain practical experience on using the specified protocols and bare footprints lotion system. The author of this thesis was present during the practices to assist with any questions that would arise during this process. The copies of the sampling instructions provided to the two novice collectors were identical, with instructions to follow the outlined procedures until the target number of samples were recorded. During the sampling process, none of the collectors were allowed to be present during sampling done by each collector. Thus, each collector was instructed record control bare footprints individually at different times (as per the availability of each participants).

5.3.2 Sample Processing

Once all the samples had been scanned using the same technique indicated in chapter 4, section 4.3.3, the resulting images were appropriately labelled and saved in TIFF format. The bare footprints sampled by the three collectors were all measured by the expert randomly, each time measuring a different sample from any of the three sets. The images were measured using the Reel method (Reel et al. 2012) and the resulting quantitative data derived from the three sets of data were entered in Microsoft Excel (version 365) for storage. A total of seven linear measurements (five toe lengths and two width measurements of heel and ball of foot, Figure 4.3) were captured from each bare footprint.

5.4 Statistical analysis

The three groups of data from the collected by the expert and two novice collectors were analysed using SPSS software version 24 and '*R'* statistical computer programming language version 3.3.2. For the statistical analysis, the three subjects (expert and two novice collectors) were set as the in independent variable (IV) and each toe length were set as the dependent variables. In total, there were six depended variables (DV). The datasets containing missing cases were excluded from this analysis, for example, TL5 was not included. The descriptive statistics were compiled using combined measurements (from expert, novice 1 and novice 2) for each toe length (TL1-TL4) and the ball and heel width (WB and HB, respectively). For example, the mean and standard deviations were used to assess the quantitative measurements. The assumption of normality was assessed for the data groups using the Shapiro-Wilk test. The distribution of the data was also inspected using histograms and Q-Q plots, before proceeding to analyse the data using a one-way analysis of variance ANOVA to compare the effect of the subjects on the toe length and width measurement differences between the three groups. The effect size was calculated using omega squared (ω^2). According to Olejnik et al (2004), omega squared (ω^2) is calculated using unbiased estimators of the variance components associated with the sources of the variations in the data, as opposed to other effect size estimators such as the eta squared effect size estimator, which tends to be biased. The omega squared effect size is less biased for estimating effect sizes in small samples. According to Murphy et al. (2014) and Field (2013), the omega squared effect can be interpreted as follows; small effect (ω^2 = 0.01); medium effect (ω^2 = 0.06); and large effect (ω^2 = 0.14). The equation used to calculate the omega square is presented below (Field 2013);

$$\omega^2 = SS_M - (df_M)MS_R / SS_T + MS_R$$

Equation 5. 1 The Omega Square Effect Size Equation

- SS_M denotes to model sum of squares.
- df_M denotes to the degrees of freedom for the effect.
- SS_T denotes to the total sum of squares.
- MS_R Denotes to the residual of the mean square.

In addition to the ANOVA, notched box-and-whisker plots set to 95% confidence interval (CI) were constructed to visually assess the level of association in the median values between the expert and the two novice collected datasets.

5.5 Results and Discussion

The results from the Shapiro-Wilk test indicated that all three datasets sampled by the expert, novice 1 and novice 2 were normally distributed $p > .05$. Visual inspection of the Q-Q plots and histograms also confirmed the data was normally distributed. The summary of the descriptive statistics are presented in Table 5.1.

Descriptive Statistics						
Subject	**Mean (mm)**	**Minimum (mm)**	**Maximum (mm)**	**Standard Deviation**	**Range**	**Skewness**
Expert TL1	228.403	209.4	253.5	17.9292	44.1	0.392
Novice 1 TL1	228.5	209.6	253.2	17.8534	43.6	0.37
Novice 2TL1	229.067	209.7	254.3	17.7867	44.6	0.423
Expert TL2	227.5	209.3	254	19.2788	44.6	0.38
Novice 1 TL2	227.364	208.8	253.7	19.4057	44.9	0.349
Novice 2TL2	227.363	209.5	253	19.0561	43.5	0.351
Expert TL3	220.058	202	248	19.5558	46	0.449
Novice 1 TL3	219.95	202.1	247.8	19.6493	45.7	0.435
Novice 2 TL3	220.078	202.2	247.8	19.4839	45.6	0.439
Expert TL4	210.403	192	236.2	18.139	44.2	0.432
Novice 1 TL4	210.317	191.5	236.1	18.0734	44.6	0.425
Novice 2TL4	210.617	192.2	235.9	17.8085	43.7	0.413
Expert WB	91.669	78.9	98.9	7.5891	20.1	-1.196
Novice 1 WB	91.678	78.5	98.6	7.8257	20.2	-1.235
Novice 2 WB	91.514	78.6	98.6	7.6911	20	-1.205
Expert HB	47.122	41.5	52.8	3.8524	11.3	-0.028
Novice 1 HB	47.328	41.4	52.7	3.855	11.2	-0.287
Novice 2 HB	47.369	41.9	52.8	3.8139	10.9	-0.065

Table 5. 1: Summary of the descriptive statistics showings all three subject (expert, novice 1, and novice 2) showing TL1, TL2, TL3, TL4, WB, and HB measurements

The ANOVA indicated that there was no significant effect at the $p < .05$ level between the expert, novice 1 and novice 2, for the measurement of TL1, $F(2,15) = .002$, $p = .998$, $\omega = 0$. There was also no significant effect between the three subjects and dependent variables (TL2, TL3 and TL4) measurements at the $p < .05$ level, $F(2, 15) = .000$, $p = 1.00$, $\omega = 0$. For the width measurement WB, the results also suggested no significant effect at the $p < .05$ level between the expert, novice 1 and novice 2, $F(2, 15) = .001$, $p = .999$, $\omega = 0$. The remaining heel ball (HB) measurement indicated that there was also no significant effect at the $p < .05$ level between the subjects for the HB measurement $F(2, 15) = .007$, $p = .993$, $\omega = 0$. The F statistic values for all measurements (TL1, TL2, TL3, TL4, WB and HB) were compared to the F-distribution table at alpha = .05 and the result indicated a critical F-value of 3.6823. According to Field (2013), if the F-ratio obtained from an ANOVA is smaller than the F critical value, the null hypothesis should be retained. The F ratio from all the interactions between the subjects

and measurements (Expert, Novice 1 and Novice 2 vs TL1, TL2, TL3, TL4, WB and HB) is not likely to occur by chance at alpha = .05. Therefore, the null hypothesis is retained because there is no sufficient measurement discrepancies to conclude that there is a difference among the means for the three subjects. Cohen (2012), indicates that effect size can also be understood as the amount of average distribution at the 50th percentile. Therefore, if the effect size is equal to 0, this indicates that the distribution between the groups overlaps completely suggesting that there is no difference. According to Field (2013) and Lakens (2013), omega squares (ω^2) is less biased and has been suggested to correct the bias observed when eta squared is used. Lakens (2013), further indicates that eta squared is an uncorrected effect size estimate which only provides the variance explained based on the sample, instead of estimates based on the entire population. These ANOVA results are substantive, suggesting that the instructions were clear and that the novice collectors were able to collect comparable data. The summary of statistical results are presented below in Table 5.2;

		Measurement					
		TL1	TL2	TL3	TL4	WB	HB
Subjects	Expert	✓	✓	✓	✓	✓	✓
	Novice 1	✓	✓	✓	✓	✓	✓
	Novice 2	✓	✓	✓	✓	✓	✓

Table 5. 2: Results indicating the one-way ANOVA analysis of the between three subjects (Expert, Novice 1 and Novice 2), ✓ denotes to no statistically significant effect ($p > .05$).

The results for the notched box-and-whisker plots for TL1 (expert, novice 1 and novice 2), indicated that all the data from the three collectors overlapped, with median values indicating no significant difference (Figure 5.1 and 5.2).

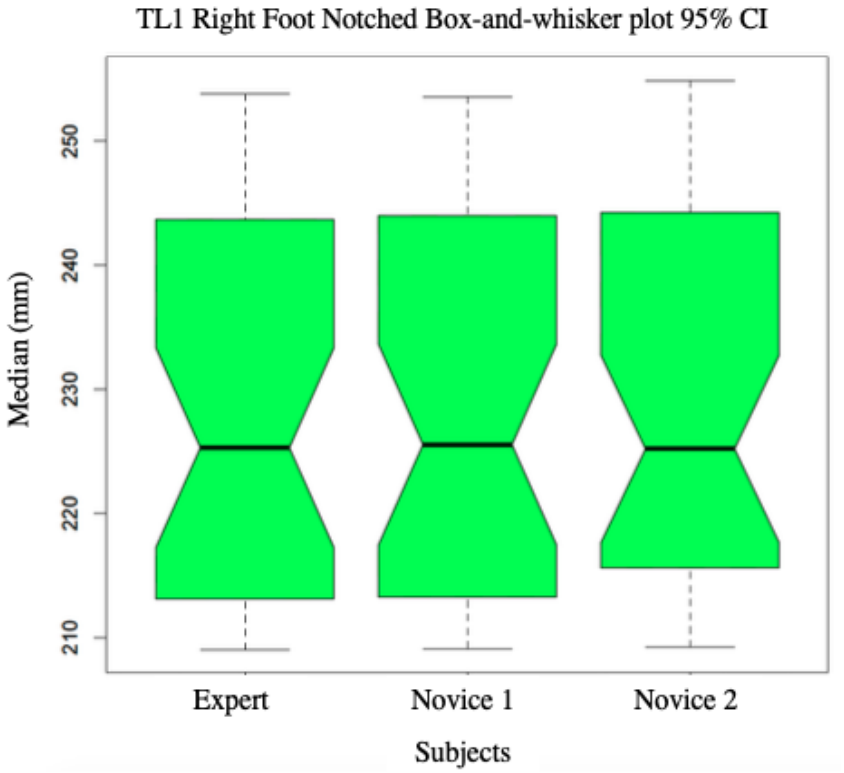

Figure 5.1: Notched box-and-whisker plot, illustrating side-by-side comparison of the median and confidence interval (95%) of Toe Length 1 (right foot) across the three subjects

According to Wells and Layne (2017), the notched box-and-whisker can be used to illustrate the difference between the median values. For example, if the notches for two or more median values fail to overlap then, the medians are significantly different from each other. Hozo et al. (2005), indicates that the mean and the variance (SD) only shows the pooled values but, does not provide the measure of the central tendency. Thus, the median is more robust at measuring central tendency in the three data sets. Nuzzo (2016) also notes that notched-box-and-whisker plots are effective at conveying key information of numerical datasets. The notched box-and-whisker plots utilises the median and interquartile spread that is robust regardless of any presence of outliers or skewness (Field 2013). In addition, if the notches overlap, there is agreement between the subjects. The notched box-and-whisker plots below indicates the results from toe length 2 (Figure 5.2). The TL2 results, indicated notches that overlapped each other

between the three subjects. Furthermore, the interquartile (50% of the data) for TL2 was shared by all three subjects (Figure 5.2)

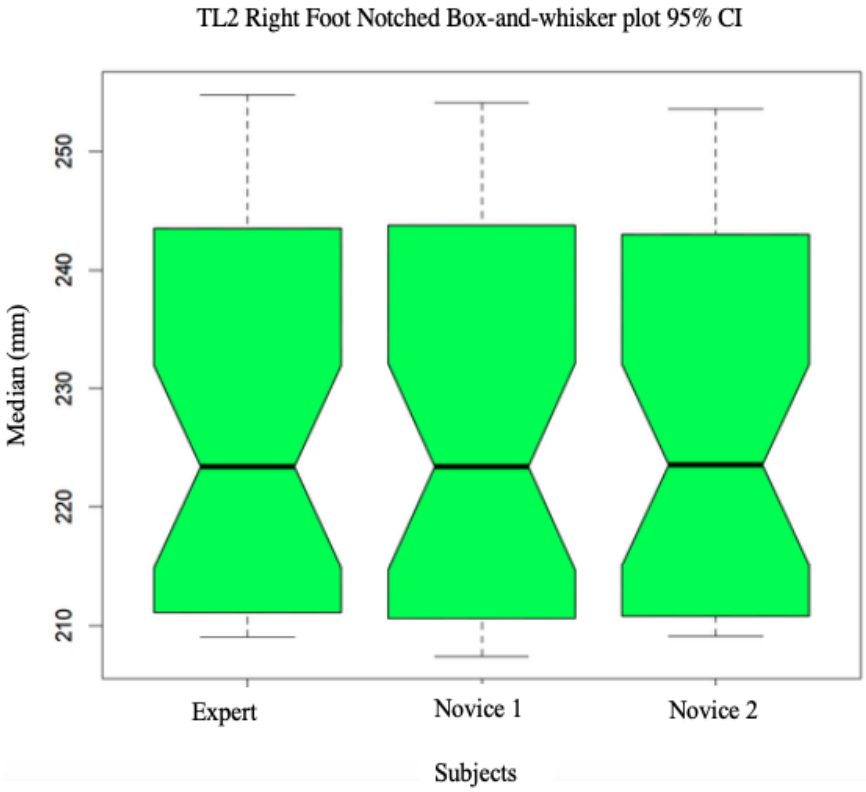

Figure 5. 2: Notched box-and-whisker plot, illustrating side-by-side comparison of the median and confidence interval (95%) of Toe Length 2 (right foot) across the three subjects.

The results for TL3 right bare footprints, indicated interquartile values, overlapping notches and median values that were shared by the three subjects (expert, novice 1 and novice 2). The lower and upper whiskers also displayed values that are close to each other (Figure 5.3). However, the notches for all the collectors displayed a median, upper-and lower-whiskers nearly identical but slightly differed (please see Figure 5.3 for illustration). The results for TL4 (Figure 5.4) displayed notches that also overlapped for all the subjects.

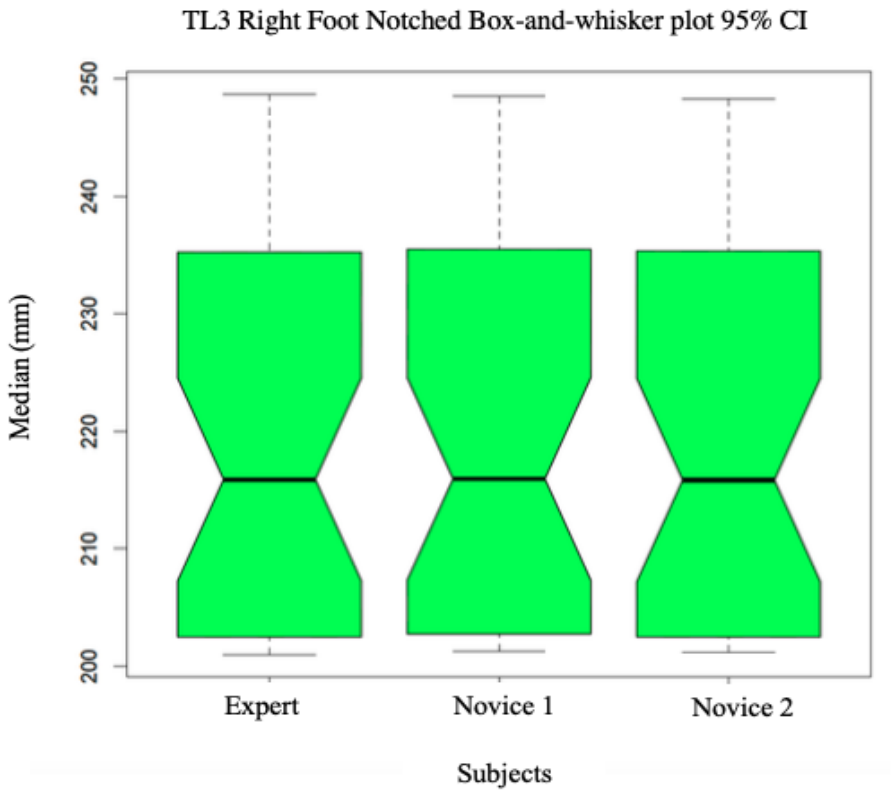

Figure 5. 3: Notched box-and-whisker plot, illustrating side-by-side comparison of the median and confidence interval (95%) of Toe Length 3 (right foot) across the three subjects.

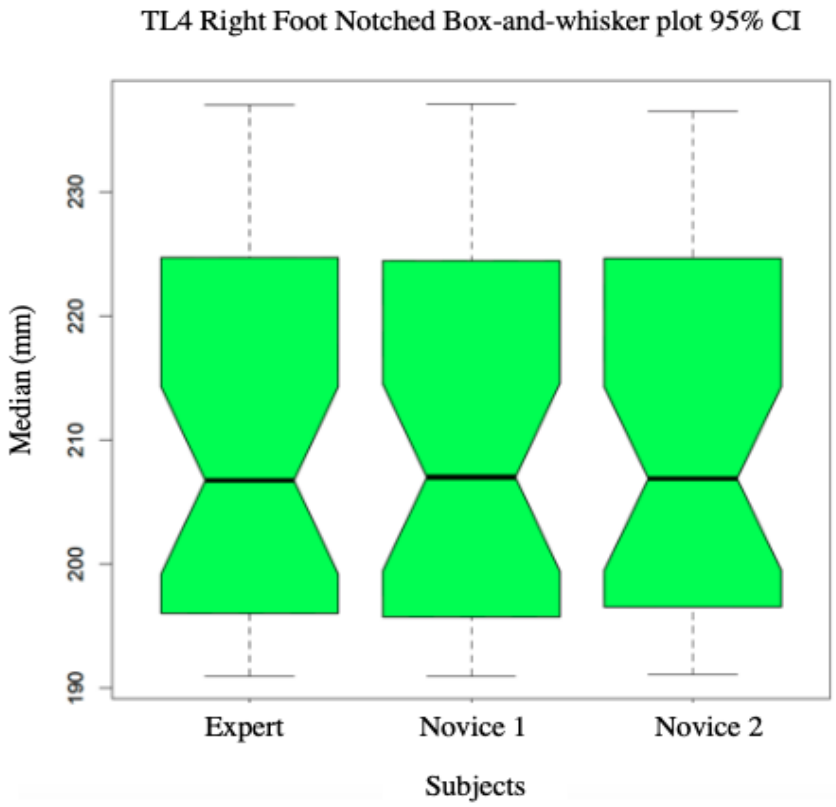

Figure 5. 4: Notched box-and-whisker plot, illustrating side-by-side comparison of the median and confidence interval (95%) of Toe Length 4 (right foot) across the three subjects.

The overall results for the notched box-and-whisker plots indicated that there was no significant difference between all the median values from the data gathered by the three subjects combined.

The results from this study indicate that the two novice collectors were able to gather comparable data to the expert using the instructions. These results also indicate that there was a high level of repeatability between the expert collector and the two novice collectors data sets. The novice collectors were able to effectively interpret the instructions regardless of their academic backgrounds, knowledge, or the level of experience in bare footprints analysis. The between-subject mean values indicated non-significant values of less than ±1 mm (either way) for all the toe length measurements (TL1 to HB respectively) between the three collectors (Table 5.1). It is also evident from this study that the novice collectors managed to acquire closely related means, standard deviations and the medians, when compared to the expert's dataset. The standard deviations displayed by the measurements of all the toes indicated shared values that can be attributed to the dependent variables for all the measurements (Table 5.1). The between group standard deviation values for all the measurements (Table 5.1) also illustrated that their measurements had the same level of precision between the three subjects. These results illustrate repeatability and thus, the proposed method can be adopted. According to David et al. (1954), a small SD indicates that the values in the groups of data are relatively close to the true mean and thus, can be deemed as being precise but not necessarily accurate. Furthermore, when the combined datasets for each toe length (expert, novice 1 and novice 2) were analysed for variability, the results indicated that there was equal variance between all the combined measurements (TL1 – HB) It is indicated by Nordstokke and Zumbo (2010) that if the groups of data result in a *p*-value that is non-significant, then it is safe to assert that the null hypothesis should be accepted (there is equal variance between the group's data). In addition, the medians displayed by the notched box-and-whisker plots demonstrated that there were slight differences in the 1st and 3rd quartile spread (Figure 5.1, 5.2 and 5.3). Even though there were slight differences, all the median values and the notches (95% CI) displayed a mathematical relationship which is accurately illustrated by the overlapping notches (Figure 5.1 – 5.4) (Mcgill et al. 2016). Furthermore, there were also some slight outliers observed in the lower and upper quartile of all the notched box plots Figure 5.1 – 5.4. This is a phenomenon of repeated sampling and is insignificant. Furthermore, it does not affect the level of precision exhibited in the data sampling conducted by the novice collectors. Even though these small discrepancies were present, the overall results were the same across all three datasets. However,

there are some limitations to consider for this study. For example, it is not known whether the results are biased due to the (i) sample size, (ii) the sampling environment (Science Centre Laboratory at Staffordshire University), (iii) and/or participant bias (the participants compensating mistakes which were unintentionally instigated by the collectors) due to their exposure to the test-retest process.

This investigation could have benefited from having more subjects to collect data and more volunteers to provide their control bare footprints. It is also not known how the bare footprints sampling manual will be interpreted by other operators and more data would be needed to investigate this. For example, one of the novice collectors indicated that they had referred more to the images of the control sampling instructions, than the written instructions, suggesting that the images would potentially allow for visual learner to perform sample collection. According to Kuntze et al. (2014), visual learners are individuals who learn/acquire knowledge by seeing what they are expected to know. Once a set of images are presented, the visual learner is able to create a logical connection of what they are required to do.

5.6 Summary of key findings

The descriptive statistics indicated small mean differences that were all within 1.0 mm for the three novice collectors for all the measurements, but this was deemed to be insignificant for this study (Table 5.1). In addition, the standard deviation (SD) was equally shared between all the measurements, suggesting that the expert and the 2 novice collectors where within the same range (Table 5.1). The one-way ANOVA results indicate that there was no significant effect ($p > .05$) between the three subjects (expert, novice 1 and novice 2) for all the measurements analysed (TL1, TL2, TL3, TL4, WB and HB). This was followed by the notched box-and-whisker plots which indicated that all the data measured by the three novice collectors overlapped meaning there was no significant difference between the three subjects for all the measurements. These results provide confidence in the sampling using the lotion system. The result indicates that despite the level of experience or knowledge in bare footprints analysis, once the lotion sampling instructions are followed, the sampled footprint is fit for purpose.

5.7 Conclusion

The descriptive statistics, ANOVA results and the notched box-and-whisker plots, all illustrate the high degree of reproducibility and repeatability between the datasets. The null hypothesis is retained as there was no statistically significant effect between the three sets of data derived

from the static bare footprints gathered by three operators (one expert and two novice collectors). It can be concluded from this study that the two novice collectors were able to effectively interpret the instructions regardless of their academic backgrounds, knowledge, or the level of experience in bare footprints analysis, to acquire good quality bare footprints. Thus, the control bare-footprint sampling method/materials and instructions are indeed reliable for control sampling (provided the instructions are followed) and can be used by personnel with minimal or none bare footprints analysis experience. The outcome of this study also illustrates that regardless of the background or how the method was followed, the result was able to induce good quality bare footprints suitable for forensic analysis. However, there is a need to ensure improvements are made in order to investigate other potential variables. For example, a large dataset is required to conduct a follow-up study. This study also needs to be conducted in a non-laboratory environment (provided the place is spacious with a hard floor surface as indicated in Chapter 4 inkless shoeprint kit system) to assess if the result (good quality bare footprints) would be affected. The findings of this study are substantive.

The following chapter will recruit participants from three distinct racial groups and use the control sampling materials and method developed in chapter 2, to gather data for the population study of bare footprints morphologies.

CHAPTER 6: Population studies

6.1 Introduction

This chapter investigates morphological variations in the bare footprints sampled from three distinct races, namely British Caucasian; Chinese; and Indians. In addition, this chapter adopts a new approach to processing control static bare footprints (data acquisition) and a novel method and materials discussed in the previous chapters. For example, the methods will include creating toe length ratios from the overall dimensions of the footprints and quantifying the shape, as opposed to using the traditional methods of toe lengths and widths presented in chapter 1, section 1.4. The lotion system was investigated for repeatability and reliability in two stages. Firstly, a comparative analysis between the lotion system and the inkless system. The second stage investigated the efficacy and ability of novice collectors, to interpret a set of instructions on how to sample control static bare footprints using the lotion system. This chapter will adopt the proposed methods and materials developed in the previous chapters to gather large datasets of bare footprints from the races mentioned above. the term 'race' is defined in chapter 1.

Ever since forensic podiatrists and footprints researchers discovered the potential of bare footprints in human identification (particularly in the context of forensic crime science), a need has arisen to acquire new knowledge of the variations that exist in bare footprints (Gunn 1991; Qamra et al. 1980; Laskowski and Kyle 1988). Conducting such an investigation will potentially aid scientists to understand if there are inter or intra variations in bare footprints from different races. For example, if any variations exist between shapes or toe length ratios in bare footprints sampled from distinct race or population groups. There are scientists who have dedicated their research to prove that bare footprints do contain individualistic properties that are only attributed to their donor (Kennedy 2005; Kennedy and Yamashita 2007; Yamashita 2010). In addition, these studies have managed to inspire research in human identification from the footprint, creating the foundations of forensic bare footprints analysis. According to Kennedy et al. (2005b), the chance of finding two identical bare footprints from different individuals is 1 in 1.27 billion, including bare footprints from monozygotic twins. Subsequent published studies which explore the individual characteristics have investigated the extent of individual traits in their respective populations, for example, India. These studies have been mostly focused on stature estimation from the foot dimensions and sexual dimorphism from

the friction skin ridge density (Krishan and Kanchan 2012; Krishan et al. 2012; Krishan 2007). Research conducted by Igbigbi and Msamati (2002), which focused on indices and ratios, was able to identify differences in distinct races, using toeless footprints from a sample of 305 White North Americans and Black Africans from Malawi. This investigation demonstrated that race was potential factor in the differences. This study illustrated that arch ratios and indices could potentially capture population specific proportions. According to Cavanagh et al. (1987) and Razeghi et al. (2002), the arch index is defined as the ratio of the weight bearing area and other parts of a toeless foot (width and length). The foot arch ratios and indices have also been used by forensic podiatrists and bare-footprint examiners to investigate structural foot types (Qamra et al. 1980; Laskowski and Kyle 1988). According to Xiong et al. (2010), the foot arches can be characterized into three types. These types are (i) high arch, (ii) medium/normal arch and (iii) law/flat arch. In addition, the use of these variables as predictors has also been reported in a study by Cavanagh and Rodgers (1987), where they were utilised instead of the traditional toe lengths and widths which are only limited to stature estimates and individual characteristics. To date, this approach of utilising indices derived from the linear measurements, for example, from heel to tip of the longest first toe/second toe; or the ratios derived from the from heel to furthest point of the longest first toe/second toe : width of ball, or width of heel, have never been attempted or investigated in bare footprints obtained from White British, Chinese and Indian populations combined.

Advances in technology has seen the rise of two and three-dimensional scanners being used to capture footprints. However, the methods employed for sampling in these studies are unorthodox in forensic podiatry (Saghazadeh et al. 2015; Lee and Wang 2014; Lee and Wang 2015; Bookstein and Domjanić 2014; Domjanic et al. 2013). The study conducted by Domjanic et al. (2013) employed 85 geometric morphometric landmarks and semi-landmarks to capture the outline of bare footprints which had initially been scanned using a two and three-dimensional scanner. According to Bonhomme et al. (2013), the morphometric analysis of the outline for two-dimensional shapes is captured by a set of x and y pixel coordinates from each sample outline. This method is widely used by biologists to catalogue or compare morphological features between human, animals and plant species (de Silva and Throckmorton 2010; Bidmos 2008; Ruff 2002; Ball et al. 2010). The bare footprints used in the Domjanic et al. (2013) study were captured using a foot scanner and altered to allow the images to be digitised with landmarks and semi-landmarks. Furthermore, this study only utilised bare footprints that were within certain parameters (e.g. bare footprints exhibiting all five toes or

the presence of a clear morphological outline), to allow all 85 landmarks to be digitised. Even though these studies provide useful information, they also fall short to the requirements or the general methods used by forensic podiatrists. Nevertheless, the output of this study is also limited to a small geographic region, for example, this study grouped the participants into four geographic categories according to the place of their birth: Slavonian region of Croatia (n=8); France (n=10); Austria, Kosovo, Herzegovina and Bosnia (n=20); the Adriatic and the continental (n=45). The results of this investigation did not yield any useful information besides the fact, lifestyle and footwear choices play a significant part in shaping the skeletal elements in the foot. This finding has already been proved to be true as indicated in chapter 1, section 1.7. In addition, the geographical region where the sample was drawn from is relatively small, as opposed to sampling from different continents (Igbigbi and Msamati 2002). Ashizawa et al. (1995) also attempted to investigate the variations in the foot from different racial populations. This was a clinical study which investigated the foot types from three populations (Filipino population in Northern Luzon, East Javanese group from Indonesia, and the Japanese group from Japan) but did not investigate the bare footprints which are the subject of interest in this thesis. It is indicated by Miro-Herrans and Mulligan (2013) and Henn et al. (2008) that the environmental and climatic conditions can potentially influence body size, hence, why the result did not indicate whether morphological variations exist in the foot. This thesis identified such information as crucial for designing the participant recruitment criteria. However, the result of this investigation conducted by Ashizawa et al. (1995), identified that the greater the weight or body mass, the greater sexual dimorphism becomes more apparent in the foot. A similar study by Kusumoto et al. (1996) examined the contours of feet from two populations (Japanese and Filipino women). The main focus of these studies were the variations of the human foot morphology in terms of the effect and impact of wearing regular footwear on the foot. Consequently, as useful as these studies may be, they do not directly touch the area of interest in this study which is 'racial differences in static bare footprints'. However, they do provide this study with an anchor point and foundation to support that if there are morphological variations in the feet from distinct races, these will also be apparent in bare footprints.

Stavlas et al. (2005) conducted an investigation of footprints using a sample of 5,866 school children between the ages of 6-17 years and managed to categorise the footprints into six types. The six types of footprints were classed as: (1-2) high arched foot, (3-4) normal foot variants, (5) low arched foot and (6) flat foot. These datasets were tested for foot type frequencies

between boys and girls (aged between 7 to 15 years) and the results indicated a significant difference influenced by developmental changes as they grew over time. Research in human evolution indicates that there are variations in the human stature between certain population groups (Miro-Herrans and Mulligan 2013; Henn et al. 2008; Carvajal-rodríguez 2008). Demographic parameters influenced by geographical regions such as population size and gene flow are believed to have influenced the variations in early and modern humans (Miró-Herrans and Mulligan 2013; Henn et al. 2008). In addition, other research into human identification confirmed that population-specific equations generated from foot measurements, or generated from the calcaneus, of certain populations can discriminate or identify associations among certain population groups (Uhrová et al. 2013; Bidmos 2006; Bidmos 2008). Furthermore, other paleoanthropological studies has indicated that hominins varied in body size and morphology (Ruff 2000, 2002, 2010; Katzmarzyk and Leonard, 1998). The fossil remains recovered from different continents together with the data gathered from previous researches suggests that environmental and climatic conditions influenced the body size and morphology in hominins and continue to influence present humans (Miro-Herrans and Mulligan 2013; Henn et al. 2008). There is also empirical evidence which suggests human size and morphology is related to variations of diet and climatic conditions (Katzmarzyk et al. 1998). The existence of different racial populations scattered around the globe indicates that climatic factors and changes in nutrition are significant in world-wide variations (Katzmarzyk and Leonard 1998; Ruff 2010; Ruff 2000; Mahakkanukrauh 2011; Bidmos 2008; Pinhasi et al. 2005). The above studies all suggest that different continents are inhabited by different races of humans which exhibit different sizes and morphologies, this includes primates (apes and monkeys). This has consequently influenced this study, the aim of which is to investigate variations of barefoot traits in three racial groups (White British, Indian and Chinese) which have never been investigated using previous and new methodologies.

For the races targeted for this investigation (White British, Indian and Chinese), geographical origin influenced the selection process and availability and accessibility to the participants. Furthermore, the variation of the bare footprints shapes belonging to these three races has never been investigated. It is clear from the literature discussed in chapters 1 and 6 of this thesis, that bare footprints analysis remains an area with many unanswered questions (e.g. inter-variation in bare footprints from different population groups). Although the inter-variations of 'bare footprints' has never been investigated in different populations, there is limited knowledge of the prevalence of certain bare footprints characteristics in distinct races as demonstrated above.

Conducting an investigation of this magnitude will provide the much-needed knowledge to prove if there are detectable variations that indicate association or disassociation of bare footprints and race, could the intelligence be applied to criminal casework?

6.2 Aims

The overall aim of this chapter is to investigate the targeted racial groups using novel methods that have never been attempted on bare footprints acquired from different population groups. This investigation will also employ R (statistical programming language) to assess if there are any inter-variations or if there are positive or negative relationships between the data from the three distinct population groups. This investigation will also conduct Principle Component Analysis (PCA) of the data generated from the toe length ratios (derived from the length and width of the bare footprints) and the morphometric landmarks (derived from the bare-footprint morphological outline).

6.2.1 Objectives

1. To recruit three distinct population groups: White British (n = 25); Chinese (n = 25); and Indians (n = 25) using the methods used in chapter 4 and 5.

2. To investigate new variables created from the population datasets to investigate the inter-variations in bare-footprint morphologies

3. To investigate the use of ratios or *x* and *y* morphometric landmark coordinates for discrimination of bare footprints sampled from different races using PCA and Model Based Cluster Analysis

6.3 Materials and Method

The same recruitment procedure listed in chapter 4 was employed in this chapter to capture and categorise the data. For this study, the previous British Whites bare footprints datasets captured in chapter 4 were also utilised together with new data gathered from the Chinese and the Indian populations who were recruited from the university campus.

The Chinese population group consisted of seven females and 18 male participants, with their ages ranging between 19 to 40 years (mean age = 29.84 years). The Indian population group consisted of five females and 20 male participants, (age range = 19 to 29 years; mean age =

23.28 years). The Chinese and the Indian students were recruited at Staffordshire University from the 2015/2017 cohort of international students. The main condition for recruiting the Chinese and the Indians was that they were not born in the United Kingdom and they had only come to the UK for studying. The participants were also asked to complete a self-assessment questionnaire to allow a computerised system to categorisation their data. This data was captured electronically and stored in Qualtrics. Each participant was asked to complete the first question which was relating to race at the beginning of the questionnaire and would allow the data to be partitioned into distinct categories (Appendix B.8). This data was double checked by the researcher to ensure that correct categories had been selected by the participants. For example, a participant from Belgium who regarded them self as being White, was not included in the White British data group unless if they were White, British and if they permanently resided in the UK. This same strict criterion was also applied to the other two races. The information that was provided by the participants, for example the place of birth and their race led to the creation of data categories which were based UK, China and India. These three race groups had the largest number of participants adequate for conducting this analysis. Following this, the data was successfully categorised into three population groups.

6.3.1 Measuring the bare footprints

Following this, the seven measurements from each bare footprints were acquired using the Reel method and measured using the software and settings described in section 4.3.1. The quantitative data was stored in Microsoft Excel (version 15.41: 171205), in data tables denoting to each race before proceeding to the next stages of calculating the ratios (as described in section 6.3.3).

6.3.2 Plotting the Morphometric Landmarks

To plot the morphometric landmarks, a total of seven landmarks (x and y pixel coordinates) were used to quantify the each bare-footprint outline. The landmark data was acquired using a two-stage process, first in Gimp Image manipulator software (for the orientation of the image), then followed by computer software mome-clic (version CLIC_98) to plot the morphometric landmarks. For the first stage, each image was first loaded into Gimp Image manipulator (software version 2.8.22) and the following settings were used; first the measurement scale was changed to measure in millimetres from pixels. This was followed by setting the layers to

boundary settings to (to access this option the layer header on the top of the screen was selected), width = 500.38 mm and height = 350.18 mm. The offset option was set to, X-axis = 150 mm and Y-axis = 53.76 mm. The settings were saved by selecting the canvas to layers option on the header option titled image. Each image was then flattened. This was followed by rotating the image until the lateral side of the foot was perpendicular with the vertical rulers and finally saved before being opened again using the morphometric software (CLIC_98). The second stage was to plot the landmarks, the image was opened using CLIC_98 by selecting the option on the header of an image illustrating a running stick man. Once the image was open, the cross-hairs option on the header was selected. Using the mouse right click, the cursor allowed landmarks to be plotted on specific certain parts of the bare footprint. Once a total of seven landmarks were plotted, the x and y pixel coordinates were saved in text editor format before being transferred and saved in Microsoft Excel (version 15.41) (Figure 6.1).

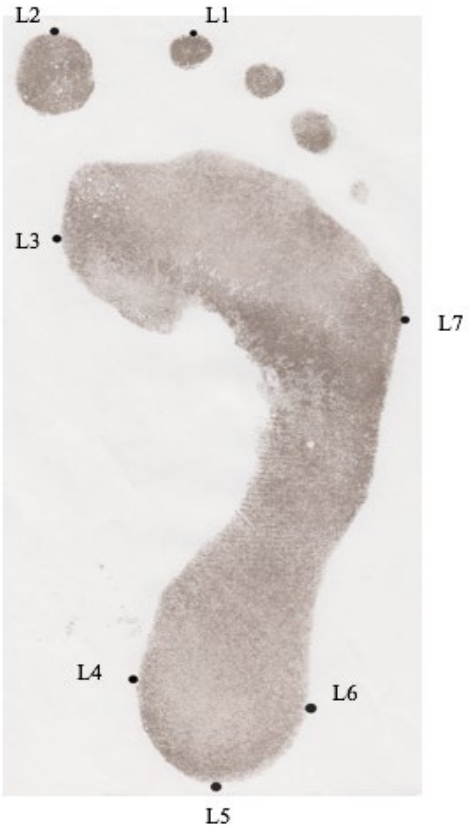

Figure 6.1: Illustration of the seven landmarks utilised to quantify bare footprints morphology based on Domjanic et al. (2013)

6.3.3 Ratio and bare footprints morphological landmarks

The ratios were derived from the two toe lengths and two width measurements. These new variables were calculated using SPSS (software version 24). The ratios used in this investigation consisted of five ratios which were a combination of widths to length or width of ball to width of heel ball. The ratios calculated included; (i) width of ball : toe length one ratio; (ii) width of ball : toe length two ratio; (iii) heel ball : width of ball ratio; (iv) heel ball : toe length one ratio; (v) heel ball : toe length two ratio. This approach was based on the study conducted by Igbigbi and Msamati (2002). The ratios were calculated by dividing the width by the length to derive to the width to length ratios, depending on which ratio was being calculated.

6.4 Data Analysis

6.4.1 Toe length measurements

The toe lengths and widths measurements were analysed using SPSS, software version 24 and R statistical computer programming language. The data was explored and assessed for normality using the Shapiro-Wilk's test. This was followed by analysing the datasets using the same method as indicated in chapter 5, section 5.4.

6.4.2 Ratios Data analysis

The ratios where analysed using 'R' statistical computer programming language (version 3.3.2). Syntax computer language was written to allow the multivariate analysis of the data using a series of combinations which included model-based cluster analysis. In order to conduct Principle Component Analysis (PCA) on the ratios and morphometric landmarks, the Kaiser-Meyer-Olkin (KMO) test of sampling adequacy was conducted to assess the strength of the relationships between the variables and if the data could allow factorability (Beavers et al. 2013). Following the KMO test, PCA was employed to the data to assess the underlying dimensions in the three racial groups. The correlation between the variables was also investigated using the pairs panels scatterplot and correlation coefficient in R. The sum of squares together with the cross–products matrices were calculated to assess the relationships between the variables. PCA was also utilised to calculate the loadings, eigen values and the percentages of the variance between the components in order to determine the relationship between the sample groups (Ball et al. 2010). The datasets were further analysed using model-based cluster plots to assess the level of relationship between the groups of data. The models employed for this analysis included (i) cluster analysis based on Bayesian information criterion

(see equation 6.2, where L is the likelihood function and m is the number of free parameters to be estimated).

$$BIC = -2\,\mathrm{Log}(L) + m\,\mathrm{Log}(n)$$

Equation 6.1: Bayesian information criterion equation

(ii) classification, (iii) uncertainty, and (iv) cluster analysis based on density (Tritschler and Gopinath 1999; Jajuga et al. 2002). Cluster analysis was also conducted on the data using the *K* – means (Appendix G.1) for illustration of the syntax code used for this analysis. Following the analysis with R, the three data sets were further subjected to post-hoc analysis. For this analysis, SPSS was used to explore and assess if the data was normally distributed. The descriptive statistics were calculated and the assumption of normality were assessed using the Shapiro-Wilk's test and the Kolmogorov Simonov (K-S) test on the ratios acquired from the three population groups. Following this, a one way between groups ANOVA was conducted and a follow-up test of the PCA.

6.4.3 Morphometric Landmarks Data Analysis

The x and y coordinate data were transformed in SPSS to create a single variable referred to as the landmark. For this process, the following equation was used to create a singular variable that encompassed both the x and y coordinates.

$$\text{Landmark} = \frac{x}{y}$$

Equation 6.2: Landmarks conversion equation.

The same data analysis process reported in section 6.3.1 was also employed on the landmark data.

6.5 Results

Table 6.1 indicates the descriptive statistics of the age, height, weight and the body mass index (BMI) for males, females, and both sexes combined in their respective population groups. In addition, the results indicate that the White British population had the highest value for the mean age (38.44 years old), followed by the Chinese population (29.84 years old). The Indian population group recorded the lowest mean age value of 23.28 years. Furthermore, the descriptive statistics also indicated that there were small differences in the means for the height of all the three population groups, which ranged between 176.35cm to 178.75cm. However, the BMI for the White British population group recorded the highest values of 26.58, as opposed to the Chinese = 23.21 and Indian = 23.71 which recorded lower BMI mean values (Table 6.1).

Race & Sex		*Age (yrs.)*	*Height (cm)*	*Weight (kg)*	*BMI (kg/m2)*
White British					
Male	*mean*	39.53	178.75	85.06	26.58
	SD	12.54	5.99	15.14	4.33
	N	13	13	13	13
Female	*mean*	37.25	164.35	72.92	27.02
	SD	14.33	4.65	15.27	5.76
	N	12	12	12	12
Total	*mean*	38.44	171.84	79.24	26.79
	SD	13.20	9.04	16.12	4.96
	N	25	25	25	25
Chinese					
Male	*mean*	31.61	176.35	72.08	23.21
	SD	8.48	5.61	8.71	2.80
	N	18	18	18	18
Female	*mean*	25.28	161.18	57.94	22.25
	SD	8.38	8.28	9.84	3.10
	N	7	7	7	7
Total	*mean*	29.84	172.104	68.128	22.944
	SD	8.77	9.37	10.95	2.86
	N	25	25	25	25
Indian					
Male	*mean*	23.30	176.39	73.85	23.71
	SD	2.79	4.72	9.03	2.45
	N	20	20	20	20
Female	*mean*	23.2	167.17	68.56	24.44
	SD	4.43	11.29	11.28	2.38
	N	5	5	5	5
Total	*mean*	23.28	174.54	72.79	23.86
	SD	3.07	7.28	9.51	2.41
	N	20	20	20	20

Table 6.1: Descriptive statistics for the three population groups, illustrating the mean, standard Deviation (SD) and sample size for Age, Height, Weight and Body Mass Index (BMI)

Table 6.2 shows the toe lengths and width (TL1, TL2, TL3, TL4, TL5, WB and HB) descriptive statistics for the three races. The standard deviation values of the three races indicated that the White British race had the highest SD values, followed by the Indians and finally the Chinese. The results in Table 6.3 also highlights the descriptive statistics for the ratios for the three races.

Measurement	White British Mean (mm)	Chinese Mean (mm)	Indian Mean (mm)	White British SD	Chinese SD	Indian SD	White British Max (mm)	Chinese Max (mm)	Indian Max (mm)	White British Min (mm)	Chinese Min Value (mm)	Indian Min Value (mm)
TL1	236.68	231.621	241.69	19.81	13.57	17.85	272.4	257.6	286.8	205.7	207.2	205.9
TL2	236.97	232.08	241.32	18.35	13.73	17.41	266.8	259.9	278.6	209.3	201.1	206.1
TL3	228.51	223.38	232.56	18.74	12.82	16.14	260.7	251.0	264.8	201.7	196.2	199.4
TL4	216.33	211.68	220.89	19.01	11.48	15.53	249.3	232.4	249.0	181.0	187.0	185.9
TL5	199.54	197.15	205.88	15.67	11.14	14.24	228.0	219.2	232.5	178.6	172.0	173.3
WB	91.79	90.22	91.84	6.45	4.27	6.13	100.8	103.0	102.1	78.4	82.2	77.2
HB	48.79	48.32	49.10	4.86	3.17	3.65	57.8	53.9	56.1	40.5	41.9	39.3

Table 6. 2: Illustrating the toe lengths and widths descriptive statistics, for the three races (White British n = 25, Chinese population n = 25, Indian Population n = 25).

Measurement	White British Mean (mm)	Chinese Mean (mm)	Indian Mean (mm)	White British SD	Chinese SD	Indian SD	White British Max (mm)	Chinese Max (mm)	Indian Max (mm)	White British Min (mm)	Chinese Min Value (mm)	Indian Min Value (mm)
WB : TL1 Ratio	0.3916	0.39	0.3808	0.02	0.01	0.02	0.45	0.42	0.42	0.35	0.36	0.34
WB : TL2 Ratio	0.3892	0.3884	0.3820	0.02	0.01	0.01	0.45	0.42	0.42	0.36	0.36	0.35
HB : WB Ratio	0.5328	0.538	0.5348	0.02	0.02	0.3	0.59	0.59	0.60	0.49	0.49	0.47
HB : TL1 Ratio	0.208	0.2088	0.2028	0.01	0.01	0.01	0.24	0.23	0.23	0.19	0.19	0.18
HB : TL2 Ratio	0.2084	0.2092	0.2032	0.01	0.01	0.01	0.24	0.24	0.23	0.18	0.19	0.18

Table 6. 3: Illustrating the ratios descriptive statistics, for the three races (White British n = 25, Chinese population n = 25, Indian Population n = 25).

The results of both the K-S and Shapiro-Wilk's tests indicated that the toe lengths and widths (TL1, TL2, TL3, TL4, TL5, WB and HB) measurements were all normally distributes ($p > .05$). The data was further analysed using the one-way between groups ANOVA which indicated that there was no statistically significant effect at alfa level = 0.05, between the three races for all the measurements. The effect size was calculated using the omega squared (ω^2), which indicated an effect size ranging between .01 to .19 for all the toe length measurements. The ANOVA results for all the measurements are presented in Table 6.4.

Measurements (Toe lengths and Widths)	One way between groups ANOVA
TL1	F (2,72) = 2.42, p = .096
TL2	F (2,72) = 2.27, p = .110
TL3	F (2,72) = 2.44, p =.094
TL4	F (2,71) = 2.42, p = .096
TL5	F (2,67) = .301, p =.741
WB	F (2,72) = 1.47, p = .235
HB	F (2,72) = .523, p =.595

Table 6. 4: Indicates the summary of the ANOVA results for the toe lengths and widths, White British n = 25, Chinese n = 25 and Indians n = 25.

For the ratios, the the K-S and Shapiro-Wilk's tests indicated that the measurements were normally distributed accept for TL2 : WB ratio (White British, p = 0.029), TL1 : HB ratio (Indian, p = 0.042 and Chinese, p = 0.041), and TL2 : HB ratio (Chinese, p = 0.044) which were not normally distributed ($p < .05$). The deviations were further investigated using Q-Q plots which demonstrated violation at both ends but with no outliers. As the sample was large enough to cope with a parametric test, a one-way between groups ANOVA was conducted and the results indicated that there was no significant effect at the $p < .05$ level between the White British, Chinese and Indian population groups, for all the ratios. The effect size indicated an effect size ranging between .01 to .52 (ω^2), for all the ratios. The summary of the ANOVA results can be found in Table 6.5.

Measurement (Ratios)	One way between groups ANOVA
TL1_WB_Ratio	F (2, 72) = 1.869, p = .162
TL2_WB_Ratio	F (2, 72) = .968, p = .384
HB_WB_Ratio	F (2, 72) = .201, p = .818
TL1_HB_Ratio	F (2, 72) = .1.509, p = .155
TL2_HB_Ratio	F (2, 72) = 1.509, p = .228

Table 6. 5: Indicates the summary of the ANOVA results for the ratios, White British n = 25, Chinese n = 25 and Indians n = 25.

Principal component analysis was conducted on the ratios data for the British White, Chinese and the Indian population data. According to Field (2013), Principle component analysis works in a similar way to discriminant function analysis or for conducting multiple analysis of variance (MANOVA). Field (2013), also indicates that principle component analysis breaks the original data in to sets of linear variates, to establish which of the linear components are present in the data. This method of analysis is suitable when for large datasets containing numerous variables such as the data in this chapter (Abdi and Williams 2010). So, five variables in total were entered in to PCA. The first three components managed to capture 97% of the total variance, and received an acceptable value on the Kaiser-Mayer-Olkin measure of sampling adequacy (KMO 0.595) for the ratios (Table 6.6). The Kaiser-Mayer-Olkin measure was calculated for all the variables combined. It is indicated by Ellonen et al. (2008) and Field (2013) that KMO test assesses the sampling adequacy of the data and it is a prerequisite of factor analysis. According to Ellonen et al. (2008), the minimum baseline for the KMO test value should be .50 to allow factorability. The KMO values obtained for this data is suitable for conducting PCA.

Components	Eigen values	% Variance	KMO
PC1	1.70	58%	0.595
PC2	1.35	36%	
PC3	0.44	03%	
PC4	0.18	0%	
PC5	0.16	0%	

Table 6. 6: The eigen values and the percentage of variance of the first 8 components and the Kaiser-Mayer-Olkin measure of sampling adequacy.

Variables	PC1	PC2	PC3
WB.TL1.Ratio	0.46297750	0.4216304	-0.43425742
WB.TL2.Ratio	0.48906398	0.3612818	0.53116533
HB.WB.Ratio	0.09984597	-0.7213285	-0.00421722
HB.TL1.Ratio	0.52816845	-0.2526453	-0.55841880
HB.TL2.Ratio	0.50748117	-0.3279616	0.46629877

Table 6.7: PCA loadings table for the ratios

The Principle Component Analysis (PCA) was constructed to visually inspect where the ratios were loaded on to the extracted components (PC1 and PC2). The PCA was also used to investigate if there were hidden variables on the principle components related. For this analysis, the highest variance in the data points was accounted with PC1, PC2 with a value of 94% (Table 6.6). Latent variables were identified on principle component 1 and 2 that seem to relate to the high correlation between the widths of ball, these are; WB:TL1 and WB:TL2 ratios. The results in Table 6.7 show the loadings for the ratios on all three components. The loadings values for the WB.TL1 and WB:TL2 ratios were 0.46 and 0.48, indicating a correlation of the toe lengths and widths between the two combined variables. In addition, the HB.TL1.Ratio and the HB.TL2.Ratio recorded the highest loadings of 52 and 50 indicating a correlation of the toe lengths and width of ball between the two combined variables on PC1 (Table 6.7). The results in Figure 6.2 illustrate that the eigen vectors for WB.TL1 and WB.TL2 were loaded on PC2, whereas HB:WB ratio, were loaded onto PC1. However, even though there are slight overlap in the datapoints, PC1 appears to suggest on differences between all three races on PC2.

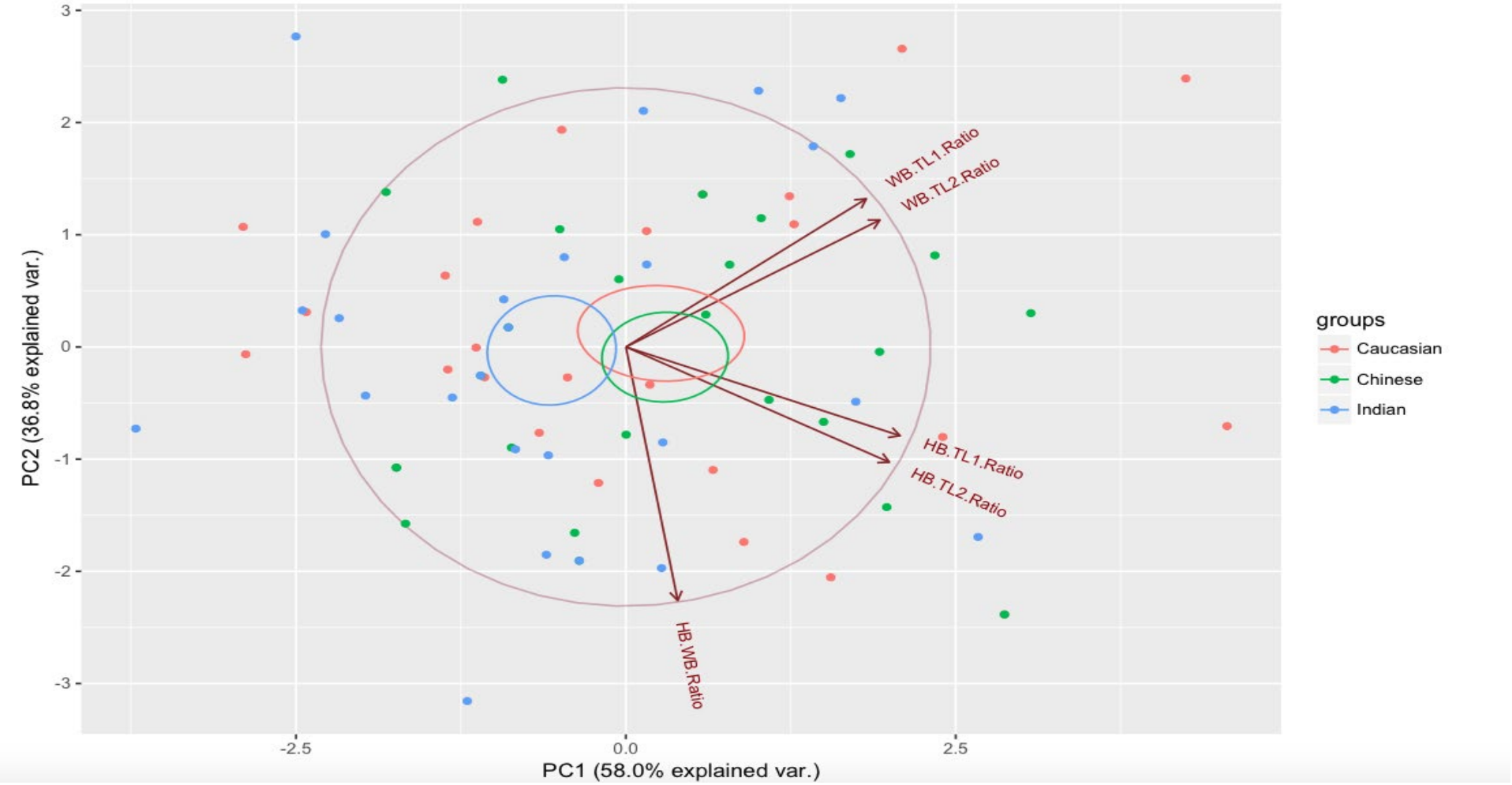

Figure 6. 2: Principle Component Biplot, illustrating each data point (for the three population groups) plotted against the values it has been assigned to by Principle Components 1 and 2. The ellipses for each population group calculated at 95% confidence interval.

The ratios were also analysed using cluster analysis thus, to conduct a visual inspection of the variables and assess how these were related to the independent variables (White British, Indian and Chinese groups). The results from the cluster analysis indicate no clustering of the combined variables to suggest no relationships between the variables and the population groups (6.3). According to Fraley and Raftery (1999) and Fraley and Raftery (2000), cluster analysis is the process of classifying data of previously unknown structures into meaningful groups. This analysis was able to utilise the MCLUST software for Model-Based cluster and Discriminant Analysis, to transform the data from a three-dimensional arrangement to a matrix in which the racial population information was lost (Fraley and Raftery 1999) (Figure 6.3).

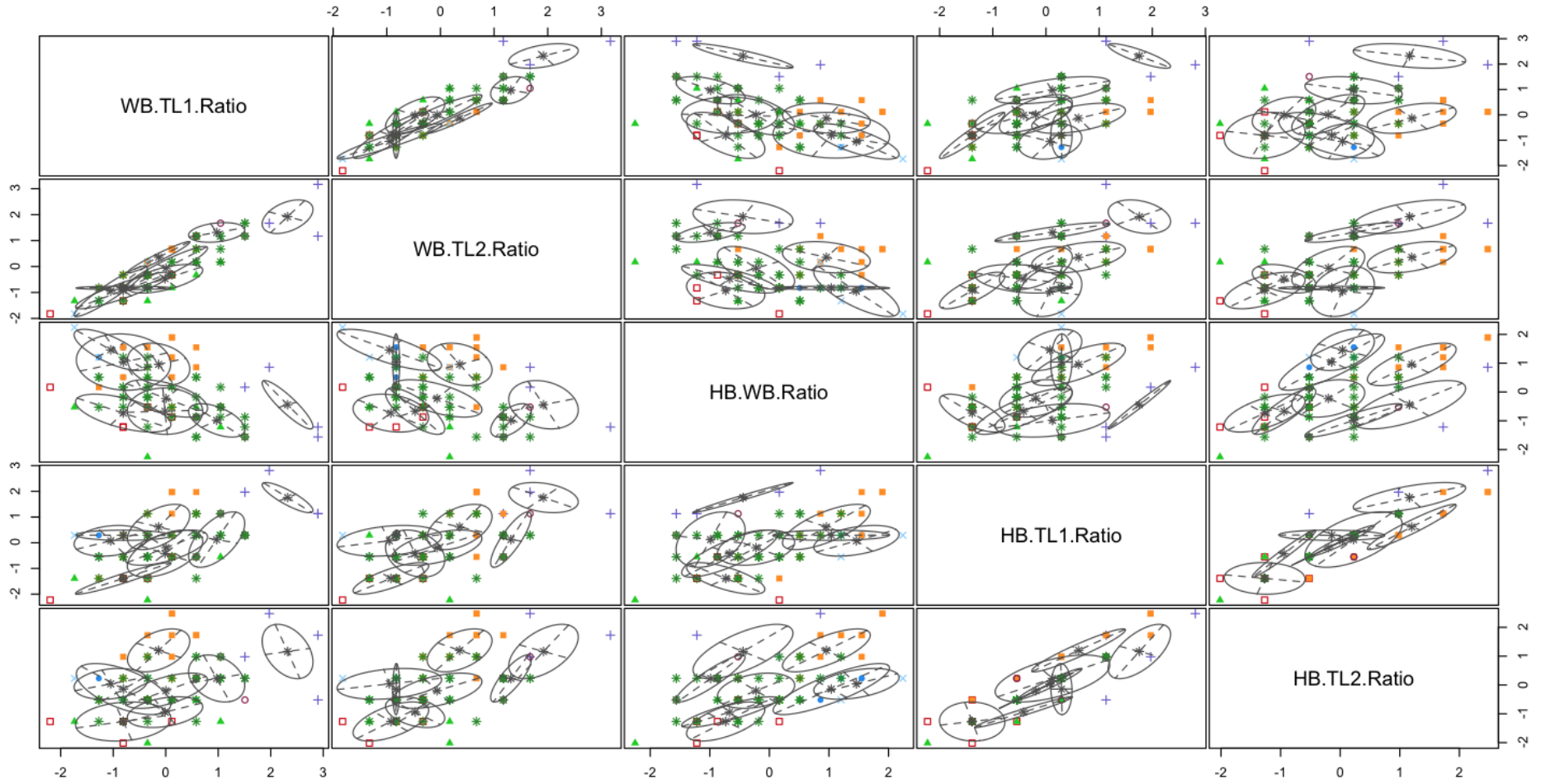

Figure 6. 3: Pairs plot illustrating the model-based classification results for the combined ratios (WB.TL1, WB.TL2, HB.WB, HB.TL1 and HB.TL2 ratios)

PCA was conducted on the data derived from the seven landmarks (Figure 6.1). The results in Table 6.8 indicates the eigen values and the percentages of variance for the first seven components for the landmarks PCA. The first two components which retained much of the variance of 88% for principal component 1 and 2, received an acceptable value on the Kaiser-Mayer-Olkin measure of sampling adequacy (KMO 0.783).

Components	*Eigen values*	*% Variance*	*KMO*
PC1	1.45	64%	0.783
PC2	1.14	24%	
PC3	0.78	05%	
PC4	0.70	0%	
PC5	0.58	0%	
PC6	0.45	0%	
PC7	0.41	0%	

Table 6. 8: The eigen values and the percentages of variance for the first 7 components and the Kaiser-Mayer-Olkin measure of sampling adequacy.

The results from the biplot indicates that the eigen vectors (directional arrows indicating the loading of each variable) for landmark 1 and landmark 2 are plotted on the same dimensional space for PC1 and PC2 (Figure 6.4). Their loadings in relation to positioning on PC1 and PC2, indicates a relationship, for example, landmark 1 and landmark 2 (toes 1 and 2). The biplot results also indicated that the landmarks 3 and 7 (width of ball), were plotted on the same dimensional space for PC1 and PC2. The remaining landmarks 4, 5 and 6 (heel), were located on/near the same alignment due to their locations on the bare footprints (as indicated by the eigen vectors; Figure 6.4). The results also indicate associations between certain bare footprints characteristics. For example, landmarks 1 and 2 are associated with the toes, landmarks 3 and 7 and associated with the width of ball, and landmarks 4, 5 and 6 were associated with the width of ball. The latent variables identified on PC2 are variables related to the landmark coordinates of the toes 1 and 2, followed by the width of ball which were loaded on to PC1. The overall results suggest that the British White is deferent to the Indians; and Chinese are not different to either the White British or Indians (Figure 6.4).

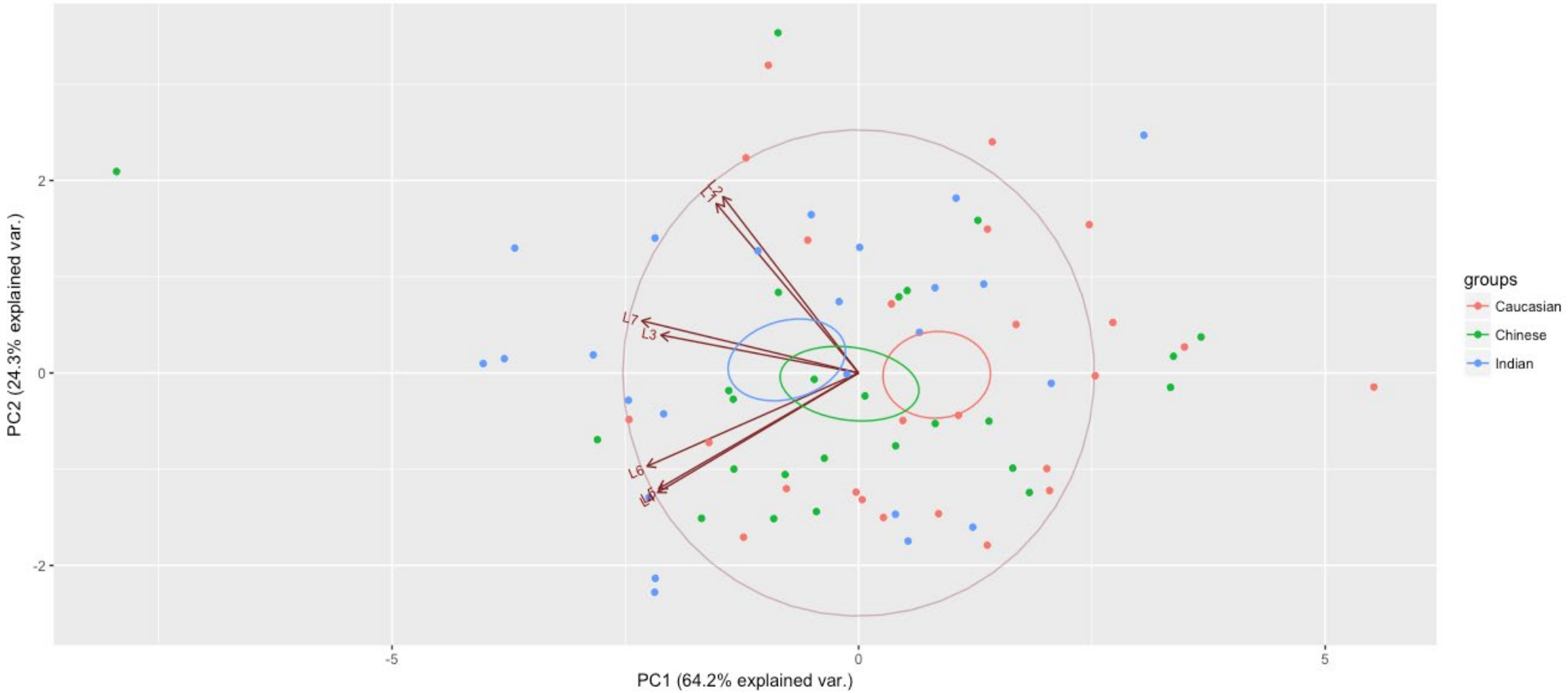

Figure 6.4: Plot, illustrating each data point (White British/Caucasian, Chinese and Indian races) plotted against each value assigned by principle component 1 and 2. The ellipses for each population group calculated at 95% confidence interval.

It is indicated by Webster and Sheets (2010) that morphological landmarks are defined as points of correspondence on each specimen that match between and within populations, or equivalently, biologically homologous anatomical loci recognisable on all specimens in a study. The difference between landmarks and linear measurements is that, landmarks only measures the two-dimensional *x* and *y* coordinate positioning on a specimen. Thus, to allow the use of landmarks, it was very important to plot the coordiantes on the same morphological features. According to Macleod and Macleod (1999) and Bonhomme et al. (2013), the landmarks need to be homologous (having the same structure, same position or same relation) between the samples. If the landmarks fail to share homologous features, then geometric information realting to the bare footprints will not be captured. The landmarks utilised in this study were reliant on both landmark and morphological features. Thus, the seven landmarks (landmark 1, landmark 2, landmark 3, landmark 4, landmark 5, landmark 6 and landmark 7; figure 6.1) derived from the three population groups was analysed using model-based cluster analysis. The results indicated clustering to suggest three distinct population groups. For example, landmark 1 and landmark 2; landmark 1 and landmark 3; landmark 1 and landmark 4; landmark 1 and landmark 5; landmark 1 and landmark 6; landmark 1 and landmark 7, indicated the highest discriminatory power, by displaying three clusters indicating three distinct population groups (red squares denote to White British, blue dots denote to Indian population and the green triangle denotes to Chinese population group). The results of the cluster analysis also identified landmark 2 and landmark 3; landmark 2 and landmark 4; landmark 2 and landmark 5; landmark 2 and landmark 6; landmark 2 and landmark 7 to also show three clusters denoting to the three population groups. The cluster analysis, also illustrated that from landmark 4 the datapoints from the three population groups were starting to become clustered, which indicated that the three landmarks (landmark 4, landmark 5 and landmark 6) were less discriminatory when compared to each other. Overall, the results of this cluster analysis, illustrates that landmark 1, 2, 3 and 7 had the highest discriminatory power when compared to landmarks 4, 5 and 6 (Figure 6.5).

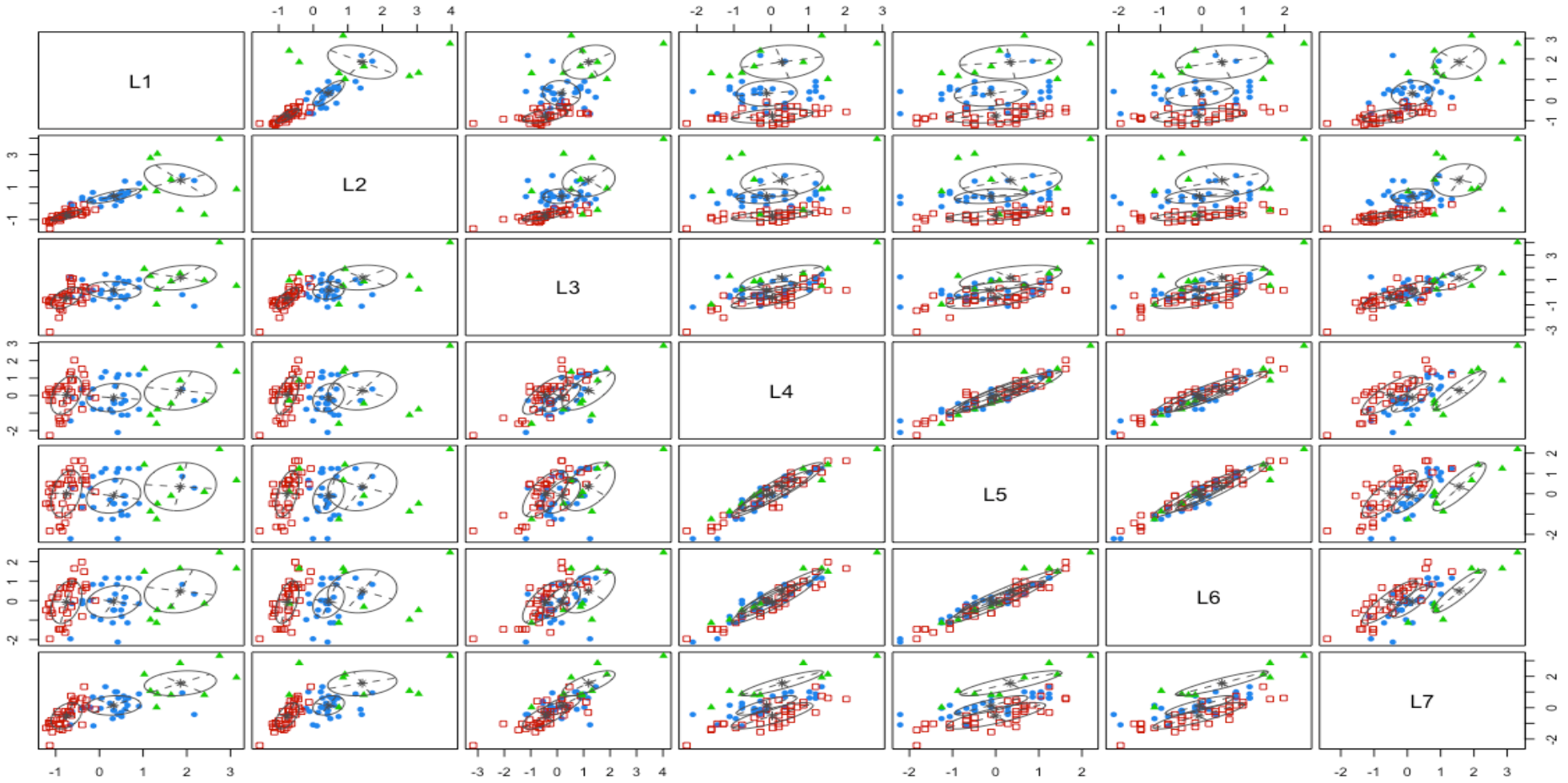

Figure 6.5: Pairs plot illustrating the model-based classification results for the seven morphological landmarks combined (L1, L2, L3, L4, L5, L6 and L7. The White British population is denoted by the red squires, the Chinese population is denoted by the green triangles and the Indian population is denoted by blue dots.

6.6 Summary of key findings

The Reel measurements (Table 6.6) where investigated using a one-way ANOVA and the results indicated that there was no statistically significant difference between the three populations. Principle component analysis was conducted using the ratios data and the overall results and demonstrated overlap between the three races, indicating no difference in the ratios. This outcome suggests that ratios are poor for discriminating race. Post-hoc tests were conducted using model-based cluster analysis and the results also confirmed that the ratios did not contain population specific characteristics that could be associated their respective population (Figure 6.3). These findings suggest that linear measurements acquired using the Reel approach only contain the variance of a single parameter in each measure as opposed to morphometric landmarks which account for more than one parameter in a single measure. This was highlighted when the landmark data was analysed using PCA. The results appeared to suggest there was differences between the White British and the Indians, but the Chinese subjects did not differ with White British and the Indian subjects. A further investigation was conducted using model-based cluster analysis and the results also confirmed that there were differences between there three races, when landmark data were used to discriminate race. These findings suggest that there is relative proportionality within bare footprints morphologies that is preserved across foot size, age or sex within a cluster of people, and these have been maintained in the three races sampled in this study.

6.7 Discussion

The main challenge in this study was the recruitment of participants. For the recruitment of participants, the three population groups presented different challenges some of which were specific and influenced by culture. For example, some participants were more forthcoming and eager to participate as they had clearly understood the aim of the research and others did not feel comfortable volunteering because part of the data sampling process involved removing their shoes, this was expected. Nonetheless, these three races were targeted because they were identified as the largest homogenous populations present at Staffordshire University.

This investigation was faced with a supervised problem, in that the categories of the data were known before the analysis. This investigation assessed if discriminant analysis could be adopted to answer the question of whether bare footprints can be used to identify a member of a population. After investigating different techniques of analysing data, the morphometric

landmarks approach was adopted as it was more effective than processing linear measurements. Traditionally, morphometric data is analysed using Proscrutes analysis. However, in this case, principle component analysis was adopted for this analysis. According to Ball et al (2010), Procrustes analysis involves the superimposition of all the landmarks (x ; y pixel co-ordinates) to form an alignment of all the points to identify characteristic contours. When this method was applied, it failed to indicate any population specific morphological variations or characteristic contours. Thus, this approach was abandoned for a more robust Principle Component Analysis and Model-based Clustering. Principle component analysis (PCA) was adopted because it is effective for analysing large datasets. According to Abdi and Williams (2010), PCA breaks the original data in to sets of linear variates, it also identifies orthogonal components which may identify latent variables that underlie multiple measurements, making this approach suitable for large datasets containing numerous variables such as the data gathered for this study. The 'R' statistical program proved to be effective at analysing the data using a range of multivariate analysis tests. The ratios and landmark data illustrated high positive and low inverse correlations which led to a problem of multicollinearity. According to Perez (2017), multicollinearity exists among the predictor variable when the variables are correlated between themselves. This problem occurs when the data contains two or more covariates or in multiple linear regression. Multicollinearity can potentially have an effect on the sums of squares, predictions, regression coefficient, fitted values and other parts of linear regression. Perez (2017), indicates that PCA can sometimes fail to process data affected by multicollinearity. To overcome this problem, the data were first normalised by scaling and centring the data. This was done in R software by running a syntax code to subtract each variable mean (from all the variables) and replacing it with a new mean of zero (Kabacoff 2015). The scale was then divided by the standard deviation so that one variable does not have influence over the other principal components. This is because some of the variables will have a large variance and some will have a small variance. Hence, in order for PCA to capture the maximum variance, only the large variances are loaded on to the Principal Components. It is evident from the principal component analysis that there was some useful information relating to the relationships between the variables from the three races or populations (Figure 6.2). The results show that the variances detected in PC1 = 58% and PC2 = 36% suggests that there are no differences in the three races. However, when a follow-up one-way between groups ANOVA was conducted on the ratios and the linear measurements of the toe lengths and widths, there was no statistically significant effect ($p > 0.05$) between the variables used to represent the three population groups (Table 6.4 and Table 6.5). The ANOVA results for the toe lengths TL1

to TL5 including the widths WB and HB, all indicated that there was no statistically significant effect ($p > 0.05$) between the three races. These results indicate the limitations of SPSS as opposed to model based cluster analysis in R with identified cluster attributed to race.

The k-means were also used to assess if there were some relationships in the data to suggest distinct races. In addition, cluster analysis was also conducted using the k-means, by performing on the data an iterative relocation with the sum of squares. According to Berger and Pericchi (1998), the k-means can potentially increase the multivariate normal classification likelihood if the covariance matrix is identical to each principal component and proportional to the identity matrix. This model was selected on the basis that it applies a Bayesian model selection through the Bayes factors and posterior probability model. Following this analysis, MCLUST enabled the creation of a pairs-plot which identified three clusters suggesting the three population groups on the landmarks data. When the same method was employed on the ratios, there was no evidence of clusters. The overall analysis of the ratios did not identify any features that were useful for identifying race origin of the donors within the three population groups utilised. However, for the landmarks, cluster analysis identified that landmark 1, landmark 2 and landmark 3 contained the most strength for identifying population differences and identifying race within the data utilised in this study. These results indicate that the second toe landmark 1, and its position in relation to the first toe landmark 2, landmark 3 and landmark 7 (width of ball), width of heel and rearmost point of heal was useful for identification of race origin (within the limits of the three populations utilised in this investigation). Landmark 4, landmark 5 and landmark 6 were excluded from this analysis because they are not showing anything of interest, but, landmarks 1, landmark 2, landmark 3 and landmark 7 (resembling a partial print exhibiting the toes and width of ball) could identify racial origin using model-based clustering. This means that the heel does not illustrate strong population specific information when compared to the forefoot features (landmark 1, landmark 2, landmark 3 and landmark 7; Figure 6.5). The model applied for this investigation was set to conduct the analysis at 95% CI. In addition, the results observed in this study are supported by the findings in the investigation conducted by Igbigbi and Msamati (2002). These authors found that there are population specific traits in of bare footprints which are attributed to the race (observed in the Back African and the White American races). This study went further to use novel techniques (e.g. geometric morphometric) to map the foot, which proved to be highly effective. Even though the landmarks were able to discriminate race in the three population groups used in this study, it is currently not known at this stage if similar findings in this chapter would be

apparent upon investigating other Racial groups different to the samples adopted in this study. According to Stavlas et al., (2005), barefoot prints sampled from a population of 5 866 school children highlighted that changes in foot type was influenced by developmental changes as they grew over time but relative proportionality is maintained regardless of sex. Thus, it is imperative that more data from other population groups should be gathered and amalgamated with current data from this study to investigate this concept further using the novel methods and materials developed in this thesis. More data would be required to investigate the error rates for correct identification.

The overall findings of this study are important and contribute to new knowledge. The new control sampling methods for sampling static bare footprints using the lotion will allow for new data to be gathered globally. But, it is worth noting that the ratio relating to sex (male to female) was not equal, so there is a need to investigate further using new data. In addition, it is also worth investigating the female and male datasets separately to comprehend the full extent of the inter-and intra-variance in the distinct sexes as the samples in this study were not adequate to conduct this. These findings help to support the intelligence aspect of forensic science and potentially aid bare footprints researchers and forensic podiatrists understand population differences in bare footprint morphologies. The population datasets acquired during this study will be used to establish a database containing static bare footprints for population testing. The establishment of a bare footprints database will enable more data from other population groups to be added and new knowledge to be amassed regarding the intra-and inter-variability of the different races. The bare footprints database will provide an opportunity to forensic podiatrists, to justify why certain categories of barefoot prints belong to certain population groups. Furthermore, the establishment of a bare footprints database will enable the prevalence of certain bare footprints characteristics in questioned population groups to be known, leading to statistical methods such as the Bayesian evaluation of evidence to be possible and more reliably used on this form of evidence in judicial proceedings.

6.8 Conclusion

This study managed to gather data from three distinct races using a novel method that utilises the bare footprint lotion. Principle component analysis and cluster analysis conducted on the ratios indicated slight overlap in the data points, suggesting no differences between the three populations Furthermore, the Landmarks PCAB suggested that the White British race is

different to the Indians; and Chinese are not different to either White British or Indians. It is evident from the results that by addressing the multicollinearity problem, important information contained in the data about the variance could have been discarded. This could have limited PCA on presenting clear clusters, or the data did not contain the much-needed information to enable clustering. However, the results of this study have illustrated that there are morphological variations in bare footprints and the landmarks with the most discriminatory power are landmarks 1, landmarks 2, landmarks 3 and landmarks 7. The bare footprints characteristics which include the first toe, second toe, the lateral and medial sides of the ball managed to exhibit discriminatory information that managed to identify race in the data but additional data will be required to investigate the error of detection It is also important to note that the sample size utilised in this study was significantly smaller to samples in other related studies. Thus, more data is required to investigate the inter-and-intra variations in different population groups.

CHAPTER 7: Establishing a Static Bare footprints Databases for population testing

7.1 Introduction

The development of the lotion system enabled the main study to gather control static bare footprints from three distinct races (chapter 6). The previous chapters also demonstrated the importance of establishing reasonably affordable methods that are robust to support forensic podiatrists or researchers solve research questions. Chapter 7 explores the notion of a bare footprints database and how it would benefit forensic podiatrists and academic researches. The results obtained in chapter 6 suggests that there is potentially more that could be gained from analysing bare footprints sampled from distinct races thus, such a data repository is required. The bare footprints database being explored in this chapter will provide a platform for researchers to add new data to existing data and to conduct interrogations on the racial data to answer specific questions as needs be. This application can potentially be used by criminal investigators understand if foot morphology difference can be used as a predictor to for identifying race from unknown static bare footprints found at crime scenes

There is more to be learned from bare footprints morphologies, and if additional data is add to this data, new hypothesis testing can be conducted. For example, population groups which include the Black African, Afro-Caribbean, and White American populations. The results in chapter 6 indicated that there are morphological variations in bare footprint, linked to race and geographical origin, combined. However, following the collection and analysis of the controls from the three population groups, it was realised that an automated computer system would benefit the overall investigation process, for example, this would allow the researcher to archive and manage the quantitative data. To enable this, a robust data management system was adopted to allow for storage of the quantitative data. This process will ensure that the data gathered during this investigation is stored and available for future use. In addition, this chapter seeks to establish an automated system that reflects the quality checks mentioned in the survey responses (Chapter 3)

7.2 Forensic databases literature review

A database is defined as a computerised data management system, that allows for archived data containing numerical values to represent the frequency of features of interest in a population

dataset (Yates et al. 2011). For provenance databases, these can potentially be employed to identify a specific sample by providing a match of a known sample and of known provenance ((Birch et al. 2016; Gwinnett 2009). However, there is a difference to what 'data collection' is, or what the term refers to when compared a database. Data collection refers to groups of related data on specific individuals (Kennedy and Yamashita 2007; Kennedy et al. 2005a and Yamashita 2010). With advances in forensic science, techniques to measure and identify crime scene samples have become profound. The development of forensic databases has enabled analysis of crime scene samples to be quicker and results gathered to have a far greater meaning in court proceedings (Gwinnett 2009). According to Shirley et al. (2013) forensic databases have played a vital role in law enforcement. Databases provide a platform for investigators to conduct a comparative analysis between known evidentiary samples and reference samples achieved in a database, for the purpose of establishing the origin of the source (Gwinnett 2009; Shirley et al. 2013). Currently, databases are frequently referred to by the law enforcement to examine forensic evidence and to gather forensic intelligence. The UK has two of the largest forensic databases in the world for DNA and fingerprint samples. These are the National DNA Database (NDNAD) and the National Automated Fingerprint Identification System (NAFIS) (Gunn 2009). Since the establishment of the NDNAD, about 611,557 DNA samples from unsolved crimes were matched between the period of April 2001 and March 2016, and this number continues to grow each time with new samples being added to the database (Home Office 2017). The improvement in DNA analysis has seen criminal cases being prosecuted and exonerations for those wrongly accused (Home Office 2017). There are also other databases which focus on marks or striations such as the National Ballistics Database. According to Yates et al. (2011), the National Ballistics Intelligence Service database (NABIS) is used by law enforcement in the UK to identify and tracks recovered ballistic or firearm projectiles. This forensic database has managed to connect a firearm(s) to multiple crime scenes where the same weapon would have been discharged during violent crimes (Yates et al. 2011). There are many advantages to establishing and maintaining databases, for example, Yates et al. (2011), indicates that forensic databases have the potential to enable multi-agency cooperation across borders between different countries. For example, corporation between different law enforcement agencies across borders (Interpol, Europol), to potentially track and trace where items of evidential value have been.

According to Bowen and Schneider (2007), there are also databases for non-biological materials, for example, databases containing chemical composites of paints used by automotive

manufacturers. These databases have managed to assist greatly in cases of vehicle hit and run. This database is an open access database, meaning that private organisations can access it. This database is also available to automotive manufacturers who are able to submit an agreed number of paint samples directly into the Paint Data Query (PDQ). According to Lavine et al. (2015), if a crime involving a car results in a chip of paint is recovered, the database is able to identify the manufacturer and model of the vehicle(s) involved in the crime provided a control sample of the paint (colour coat or the primer) is present in the PDQ repository. This database is now being shared by law enforcement agencies (Royal Canadian Mounted Police, German Forensic Institute and the Japanese National Police Agency) in three different countries to identify vehicles involved in crime. Bowen and Schneider (2007), indicates that since the three agencies signed a memorandum to corporate on the data gathering and maintenance of the database, it has allowed for some 1,500 paint samples to be added to the PDQ database annually. Furthermore, the realization that reference databases are useful and can provide information about the source (provided a control is stored in the repository). This has seen the establishment of new forensic databases, for example, these include handwriting (Forensic Information System for Handwriting: FISH) and inks, established by the United States Secret Service (Srihari and Leedham 2003). In 2007, the database of ink contained 9,500 inks, some of which were collected from as early as the 1920s (Bowen and Schneider 2007).

For footwear evidence, there is the National Footwear Database which contains footwear prints found at crime scene and exemplar footwear prints and images from suspect shoes (TreadMatch). There is also another database which is maintained by a private organisation Foster and Freeman, which contains crime scene images of footwear and other information regarding the footwear (e.g brand, model, date of market release and the manufacturer) (SoleMate) (Shirley et al. 2013; Levin 2013). The recording of footwear marks evidence was been made possible by the *Police and Criminal Evidence Act 1984*, which was amended by *Criminal Justice and Police Act 2001* and the *Serious Organised Crime and Police Act. 2005*. These legislation allows samples of DNA, fingerprints, gait and footwear data recorded from detained suspects (arrested for a recordable offence), to have their samples added to the databases. In addition, the legislations also permits volunteers to donate samples so long they provide written consent. However, collecting and maintaining a database is difficult and time-consuming.

7.3 The need for a forensic bare footprints database

There is a need to gather large datasets of bare footprints, and establishing a bare footprints database will allow the data to be stored in a single repository (Jira et al. 2015; Jira and Gwinnett 2018). A bare footprints database will allow population differences in bare footprints morphologies to be explored to benefit research and the criminal justice system DiMaggio and Vernon (2017). Currently, there is no forensic bare footprints database in the UK to enable quicker examinations, or provide conclusive intelligence, for example, the frequency of certain bare footprint characteristics or their prevalence in UK populations (Jira et al. 2015; Jira and Gwinnett 2018a; Jira and Gwinnett 2015; Jira and Gwinnett 2018b). However, there are publications which report of a collection of 24,000 bare footprint from a heterogeneous sample (mixed populations), but no database has been made available to researchers or forensic podiatrists in the UK (Kennedy et al. 2005; Kennedy and Pressman 2003). In addition, the information relating to the criterion that was used to sample the data or whether the data was static, dynamic or which foot was sampled from the subjects remains scant. Even though this is reported to be the largest single collection of bare footprints in Canada, this data still remains limited, hence, there is a need to establish a bare footprints database to aid criminal casework or research (Jira et al. 2015; Jira and Gwinnett 2018). The population difference remains outstanding and was not investigated by Kennedy (2003; 2005). Furthermore, the court testimonials derived from these data caused controversy in the USA, which led to several court cases being appealed and some convictions being overturned (Reel 2012). It is also indicated by Reel (2012) that conclusions derived from the frequency of features or characteristics of bare footprints are questionable. Consequently, court testimonies such as those provided using data from the Kennedy footprints collection have been subjected to judicial reviews, resulting in acquittals in some cases. According to Nirenberg (2016), before evidence is presented in court, the evidential reliability should be based upon scientific validity, hence why this study was conducted. Therefore, it would be beneficial to the forensic science community, particularly forensic podiatrists if a bare footprints database was established using the approach presented in the previous chapters. This database will have the potential to test and assert the value of bare footprints; particularly placing a meaning on footprints used in court proceedings. The bare footprint database will have the potential to provide unbiased conclusions as outlined in the Codes of Conduct and Practice (Forensic Science Regulator 2016).

7.4 Aims

The overall aim of this chapter is to establish a computerised data management system that allows for control bare footprints to archived in relational tables, for example, demographic data to biological data to bare footprints data.

7.4.1 Objectives

1. To establish a database that will allow for new population groups to be added into the database; and allow extant data gathered by other researchers and forensic podiatrists to be added into the database.
2. To develop computerised data management system, that adheres to the Codes of Practice and Conduct which are set out by the Forensic Science Regulator (YEAR).
3. To establish a system that ensures the data gathered from the participants (personal information) is encrypted to prevent unauthorised access.
4. To establish data categories and relational data tables using the quantitative data from the three population groups.
5. To establish a system that is auditable to ensure data integrity is maintained.

7.5 Method and Procedure for Establishing a Bare footprints Database

Ethical approval was obtained from Staffordshire University before the data was collected (Appendix A.1 and A.2). The same data entry procedures undertaken in chapter 4 were followed in this chapter. The participants were assigned a unique reference number (UNR) consisting of the initials of their name and surname and a sequential number. The prototype database was designed in Microsoft Access Database (software version 365) and archived in a secure server at Staffordshire University. Relational data tables were created for each racial population group data. The relational data tables consist of, (a) Table 1: Biological Data (Participant Unique Reference Number, Gender, Height, Weight and BMI); (b) Table 2: Toe length and width measurements (Reel Measurements); (c) Table 3: Toe ratios (d) Table 4: Bare footprints morphometric landmarks data. In total, 12 data tables were created for the three races. The primary key on the database was assigned to the URN thus to link the tables to their respective population groups (Figure 7.2).

7.5.1 Coding for Database

Each participant was assigned a unique referencing number which was derived from the initials of the first name and surname. Table 7.1 indicates the example of how the participants name was assigned a UNR. Figure 7.1 indicates the data tables race category and the URN.

First Name and Surname	Gender (M/F)	URN Coding for Database
Peter Jones	M	PJ/1
Tom Wilde	M	TW/1
Janet Williams	F	JW/1
Tracey Longport	F	TL/1
Jann Wilson	F	JW/2

Table 7.1**:** Illustration of database coding with example names not real participants.

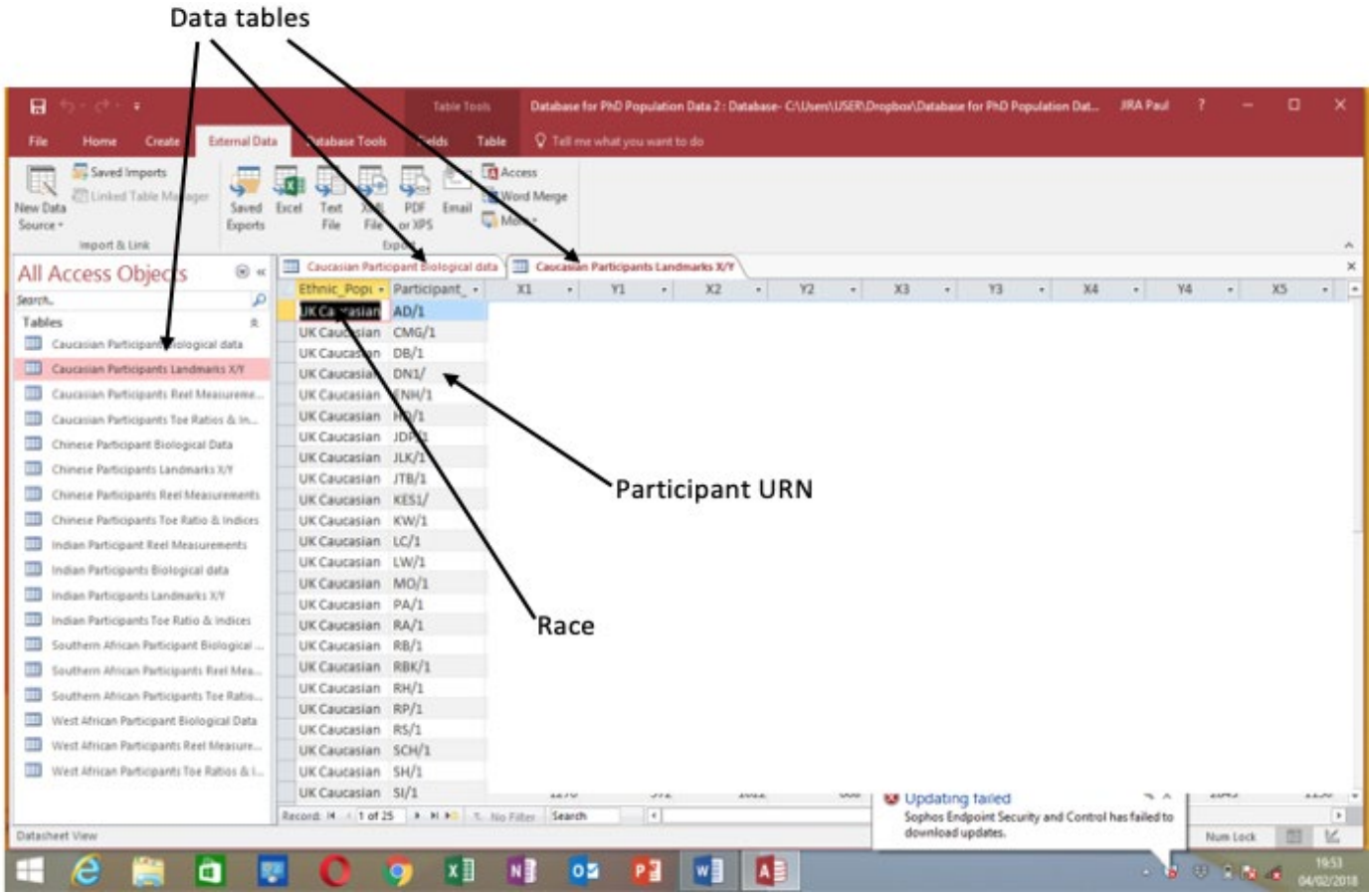

Figure 7. 1: Illustration of the Access Database Cording of The Participants

The UNR was created at the beginning of the questionnaire. This UNR allows all the data from the participants to be linked. The numerical value in the UNR column represents that only one participant has got the name that is indicated by the URN. However, if there are two people with a names and surname that exhibits the same initials, their second letter of their name can be added to the URN as indicated in Table 7.1: for Peter Jones and Paul Jira. Another coding example is Janet Williams and Jann Wilson, because both participants have the same initials, the numerical value is increased with every participant who has the same initials. The storage requirements, security, data management and access to the bare footprints data are based on the Codes of Conduct and Practice (Tully 2018). To query the data, the data was imported as a complete data table from Microsoft Access, into Microsoft Excel by selecting the 'External Data tab, followed by Export to Spreadsheet and finally choosing a destination to place the data. Once the data was inputted into Microsoft Excel, SPSS and R were utilised to analyse the data.

7.6 Results

Three relational data tables were linked to their respective race using a URN thus, to manage the biological, toe length and width measurements, ratio and the morphological landmarks data (Figure 7.1; Appendix H.2 – H.13). The bare footprint Architecture illustrates relational tables which are all linked with the UNR and the racial population group.

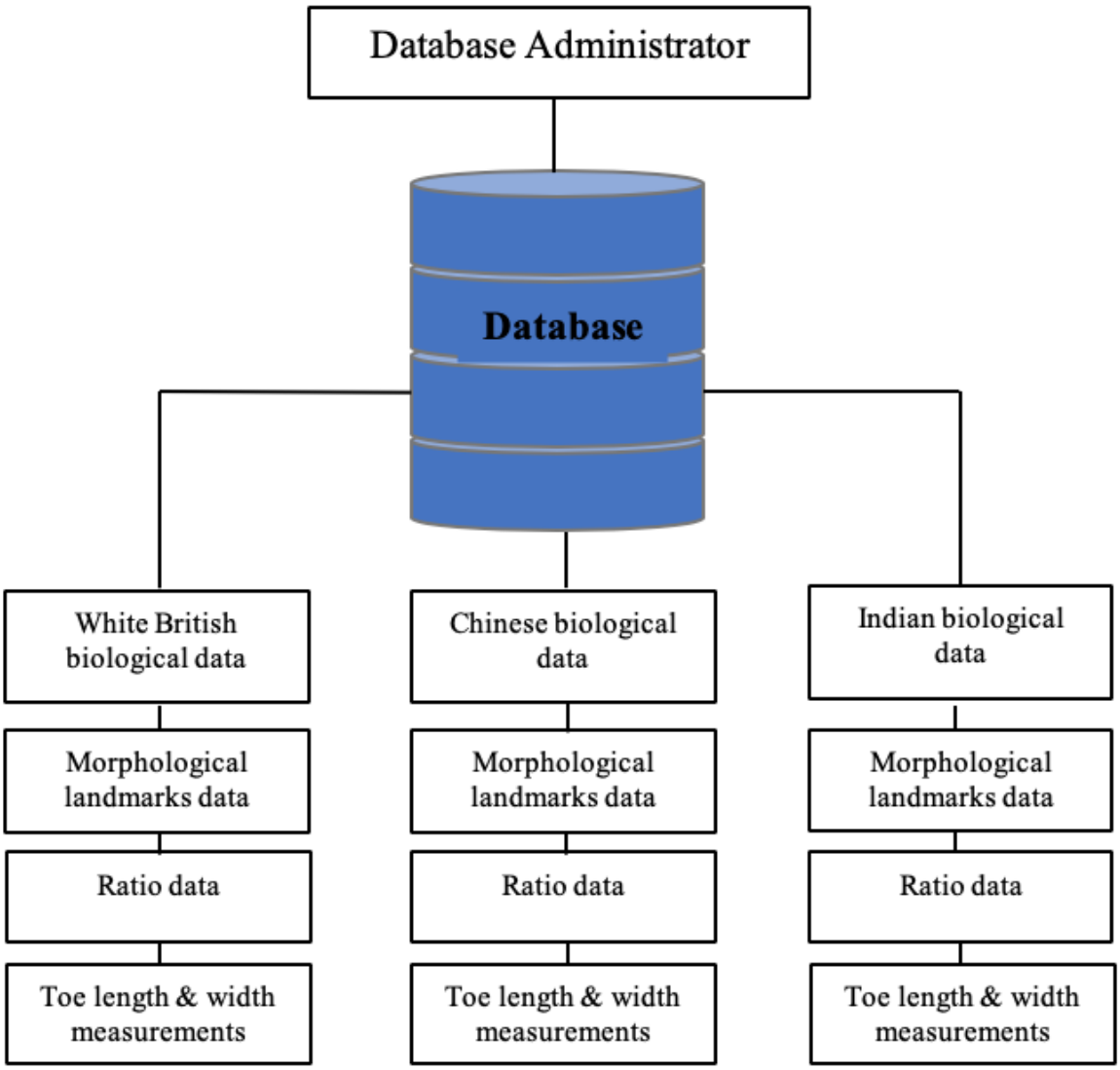

Figure 7. 2: Illustration of the bare footprints database architecture

7.7 Discussion

According to Tully (2018), it is essential that the information being captured should not be altered or if altered, the lost information should be at an acceptable level. It is also indicated by Tully (2018) that if the information being captured requires a scanner, an appropriate standard operating procedure should be established which ensures that the scanned data is not compromised. Furthermore, the Forensic Science Regulator (Tully 2018) also sets out strict guidelines on how electronic information consisting of personal data should be securely destroyed. For the bare footprints database, currently, there are only two people who can access the participants information (researcher and researcher's primary supervisor). This ensures that unauthorised individuals are unable to access the database to view or extract personal information relating to the participants. It is important that a limited number of personnel should be granted access to the database. For example, the National DNA Database is managed by the National DNA Database Delivery Unit (NDU). This unit ensures that the database integrity and quality standards are optimum, by employing less than 30 people (security cleared) to manage the day to day administration of the database. According to the Home Office (2017) limiting the number of people to only a few with administration rights will ensure the integrity of the data is maintained and if compromised, furthermore, if a problem arises, there is a chance it can be traced to the source.

Currently, the Microsoft Access Database does not possess advanced security features similar to other commercial software (e.g. Oracle or the Bluestar software: National Footwear Database). The latter programmes allow for additional design features security features that include password and administrator control to prevent unauthorised access (Geradts and Bijhold 2001; Hannigan et al. 2006). It is also indicated by the Home Office (2017) that data held on a database should be kept securely and the methods of data collection and storage should always be subjected to vigorous assessments thus, to identify flows or any inconsistencies with the database or administrator. There is always a risk of data corruption or loss, thus, this study made a backup copy which is currently stored in a secure place at the Staffordshire University premises. The hard copies of the bare footprints will be retained for future use and handled as prescribed by the Forensic Science Regulator: Codes of Practice and Conduct (Section 23.19 Control of Data [ISO 17025:2005 ref. 2.4.7] (Forensic Science Regulator 2016), which states that appropriate data control measures should be accorded to ensure that all personal information is managed in line with the code of conduct set by the FSR.

Hence, to ensure that the data management proceeds beyond safeguarding. Microsoft Access software was chosen for the prototype database because it is user-friendly. For example, it is compatible with to Microsoft Excel and/or allows for the data to be imported from Excel into SPSS querying. But, there are limitations to using Microsoft Access Database, for example, the security feature is not as advanced as other forensic databases. Therefore, to ensure the integrity of the data contained within the database, the database will not be open access until appropriate measures are taken to ensure participant personal data is protected. In the future, users who collect data using the procedure set in this thesis or data collected using the best practice published in literature will be enabled to add their data into the database.

7.8 Conclusion

This chapter established a database consisting of bare footprints sampled from three distinct races. This allowed for relational tables containing four variable data derived from each population group to be linked to their respective races, enabling the data to be easily managed. In addition, establishing a computerised data repository system of static bare footprints using the Code of Conduct and Practice set by the Forensic Science Regulator (Tully 2018), will initiate the creation of a provenance database that can potentially be used to compare known population data and unknown samples of known provenance. It is evident from this thesis that large datasets of bare footprints are required to investigate population differences in the bare footprints morphologies and the data management system presented in this chapter is appropriate.

CHAPTER 8: Conclusions and Further work

8.1 Conclusions

The work in this thesis is, in part, designed to enable ready data collection so that questions relating to population differences in bare footprints can be answered in a more thorough and scientific fashion. Particularly, this would have an impact in the area of intelligence. For example, there are indications that there are morphological characteristics that differ between the pre-defined groups of individuals sampled in this thesis. As such, this thesis has shown that there are differences in the populations investigated using the landmarks method. However, more data would be required to robustly confirm this result. The overall investigation establishes the intelligence aspect of forensic bare footprints analysis and this thesis contributes to new knowledge in that area. In the context of forensic science, bare footprints are mostly assessed to determine the probability of a bare footprint, mark or impression (two or three dimensional) found at a crime scene, belongs to a certain individual of interest. Currently, bare footprints found at crime scenes, provides limited supports relating to the intelligence, for example, stature and sex estimation but, does not provide intelligence supporting estimation of race or the probability of the individual who produced the mark. The intelligence aspect will benefit forensic podiatry as a discipline and aid the justice system appreciate the value of bare footprints if there are placed before the court as evidence. The intelligence aspect will answer certain questions not previously possible with existing data, for example, 'how probable would the individual who deposited a bare footprint at a crime scene would self-identify them self as belonging to a certain race or group e.g Indian, Chinese or white British'. Currently there are now methods that existed to answer this philosophical question. This thesis focuses more on the intelligence aspect because there is need to know about probability distributions in bare footprints sampled from individuals who would self-identify as belonging to certain races (and this is powerful in the bigger context of forensic science) and this would aid the investigation intelligence.

One of the aims of this thesis was to develop a cheaper (to the industry standard inkless shoeprint system and fingerprint ink), and generally acceptable to the population (because of its non-toxic nature) method for sampling control bare footprints. To achieve the overall aim, a new approach to sampling bare footprints using a lotion and chamois leather pad was developed and tested for reliability before being adopted for full-scale data collection. Following literature research, it was identified that the hand lotion first developed by Bond

(2013), could potentially be adopted to allow the gathering of control static bare footprints. The quantities of ingredients reported by Bond (2013), were not sufficient to produce satisfactory good quality bare footprints. Therefore, the ingredients were reconfigured to create the bare footprints lotion capable of acquiring control static bare footprints. Following the modifications to the original ingredients, the lotion was assessed and the qualitative and quantitative results suggested that the lotion system could be adopted as an alternative or could be used interchangeably with the industry standard methods. The colour and contrast results of the samples taken using the lotion were rigorously tested to ensure the quality mimics the inkless shoeprint kit or fingerprint ink. Both qualitative and quantitative results from the analysis showed that there were no quality and statistical differences between the lotion and the industry standard. These findings are significant because they provide bare footprints researchers and/or podiatrists with a safer alternative method to the existing inkless shoeprint kit which contains ferric chloride which contains corrosive chemicals (CSI Equipment 2018).

Following this, this thesis investigated the accuracy of the data gathered by novice collectors using a set of instructions. The data sampled by the two novice collectors were compared the data sampled by an expert to assess if there were repeatability and comparability in the data. The results of this investigation indicated that there was no statistically significant difference in the data gathered by the three ratters. This is significant because the lotion and chamois pad can be used by any individual, provided they are able to read the instructions regardless of their academic background. The result of this experiment is significant because the lotion system and the set of instructions can be used by someone with now experience in bare footprints analysis. In addition, the lotion system can be sent to volunteers around the world to gather data in their respective populations at low costs.

This thesis explored the existing analytical methods used by forensic podiatrists and researchers to process two-dimensional bare footprints to understand the limitations associated with such approaches. This study identified that the footprint dimensions and other specific characteristics were dominant amongst most analysis, for example, the lengths, widths of a bare footprint and crease marks (Laskowski and Kyle 1988; Gunn 1991; Kennedy et al. 2005a; Reel et al. 2012a; Krishan 2007). However, there were other studies which reported the mapping the foot, for example, the podometrics method which used a grid of longitudinal and transverse lines to map the foot (Rossi 1992). Furthermore, the literature also explored the geometric morphometric method which used a comprehensive set of 85 landmarks and semi-

landmarks (Shape coordinates), to map the footprint outline. Following this, the thesis identified seven key features on a static bare footprint that could potentially discriminate bare footprint morphologies and employed these instead of the linear measurements normally used by forensic podiatrists. The newly developed lotion system was used to sample static bare footprints from three distinct races, the White British, Chinese and Indians. The data was analysed and four sets of data were derived from the bare footprints, for example, length and width ratios, index data, linear measurements (Reel 2012), and seven morphometric landmark data.

The data was first analysed using SPSS (software version 24) before moving on to 'R' statistical programming language. Only the data the was measured on a linear scale (linear measurements) or derived from it (length and width ratios) were analysed using SPSS. The results did not suggest there were no apparent racial differences in the data. The data was then analysed using a novel approach, which analysed morphological landmarks using 'R'. The latter approach enabled the data to be analysed using Principle Component Analysis (PCA) to investigate footprint morphology differences in the three races. The findings of this investigation suggested that there were differences in the data, attributed to race. In addition, the seven landmarks plotted on each bare footprint sampled from the three races, indicated that bare footprint morphologies contain population specific classification markers that can be used to identify race within the data gathered in this study. These findings are significant, therefore, contribute to new knowledge. Furthermore, it is evident that, linear measurements acquired using the Reel method, only contained variance of a single parameter in each measure as opposed to morphometric landmarks which account for more than one parameter in a single measure. The classification markers that possessed the highest discriminatory power were identified as landmark 1, landmark 2, landmark 3 and landmark 7, meaning that a partial bare footprint could potentially yield population specific information (Figure 6.1). This is significant because if a static partial bare footprint was recovered from the crime scene, it could potentially provide useful intelligence to the investigators. The resulting data from this study was used to establish a bare footprints database containing relational data tables of biological, demographic, landmarks, ratios, and length and width measurement.

It was also identified that there were inconsistencies relating the number of repeats sampled from research or as control bare footprints from the suspect. Therefore, a tool for sampling control bare footprints was created and is described in this thesis. This thesis investigated the

spread of data, to understand what might be expected when a random control sample is sampled from the inkless system and the lotion system. Following this investigation, it was identified that 6 repeats of control bare footprints were appropriate as this allows for the average and spread of the data to be known. If the spread of the data is very narrow, then the average is a good representative of what you are likely to find at the crime scene.

The code of conduct prescribed by the Forensic Science Regulator (Tully 2018) was adopted from the initial stages of data collection, in addition to the ethics approved by Staffordshire University's Ethics Committee. This is significant because this database is founded using best practice as opposed to the process followed by Kennedy to gather samples which remains questionable, to whether ethical conduct was adhered. There is potential in this data, for example, the data can be used to answer research questions or aid forensic podiatrists with criminal casework. Furthermore, the resulting database will provide a platform to add new data to the database, allowing the data to grow.

8.2 Further work

There were many questions that arose from this study which require further work, for example, due to logistical challenges and time constraints, it would be beneficial to conduct post-hoc studies to investigate the accuracy of the data and ability of novice collectors using the lotion system. Further work to investigate the lotion system and sampling instructions will enable future studies of this nature to determine if there is comparability and reliability in the data sampled using the novel method. Conducting further work will provide clarity of whether the data sampled by volunteers (using the lotion and instruction) can be added to the bare footprints database. There are also several questions that arose from the population study, for example, if the morphological variations observed are limited to the three races sampled in this study. This question can be solved if additional race data is gathered and analysed together with the data in this study. It is therefore important to explore this further. This thesis sampled and analysed static bare footprints only, so, further work is required to investigate if morphometric analysis can be applied to dynamic footprints thus, to derive the same outcome. It is imperative to investigate this further.

Further work is also required to investigate why race differences were apparent in landmarks data only and not linear measurements. It is important to investigate if there are other

parameters that can discriminate race or suggest the existence of racial differences. In addition, it would be interesting to conduct discriminant analysis to investigate the detection error rate; therefore, further work is required to gather more data.

Further investigations are also required to assess if there are morphological differences between static and dynamic control bare footprints. This investigation will help determine if the two are comparable.

It is imperative that these investigations are conducted to assess if the landmarks approach proposed by this thesis, if applicable to forensic samples, for example, comparability between known and unknown bare footprints captured at the crime scene. Model-Based Cluster Analysis successfully discriminated the three population groups; therefore, further work would be required to investigate if the four landmarks (landmark 1, landmark 2, landmark 3 and landmark 7) could be used as classification markers to train machine learning algorithms. According to Ip et al. (2003), once a set of classifies have been identified, the k nearest neighbor learning algorithm can learn classifications by storing training examples that can be used for pattern recognition. If this works, the three population datasets can be used as templates for machine learning, however, further investigations are required to deem this applicable for research or criminal casework and more data is required. Furthermore, R proved to be robust at analyzing the population datasets, it is possible to write new syntax code to try new types of analysis on the same data.

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