A comparative study of standing fleshed foot and walking and jumping bare footprint measurements

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1. Introduction

Measurement of crime scene footprints can support the process of forensic biological profiling and the identification of unknown perpetrators [1]. This is important when epidermal ridge patterns, such as those seen in fingerprints are absent [2]. Previous research has investigated uniqueness of footprints. Kennedy et al. [3] suggested high levels of individuality with the odds of a chance match reported as one in 1.27 billion. Barker and Scheuer [2] suggested variations in footprint morphology result from three main factors: individual foot shape, method of locomotion and the substrate which the foot impacts on. With such high levels of variation, forensic examination can be undertaken to compare unknown and known footprints to support match or mismatch propositions. Furthermore, literature highlights numerous variables, such as ethnicity, age, gender, body weight and method of locomotion influencing foot morphology and footprint formation [2,4,5,6,7].

Bare footprints may be left in blood, dust, sand, oil, mud or paint on hard surfaces, such as wood, laminate or waxed floors [8,9]. If the length and width of a person's foot is measured and compared to the same measurements of their bare footprint impression, it is likely that these will not match because the foot is a three-dimensional structure and the footprint a two-dimensional impression. It is recognised by DiMaggio and Vernon [1] that hard surface footprints only represent those parts of the feet which have made ground contact. This is because foot shape is rounded at heel and toe ends and in most cases these areas would not have contributed to footprint formation, unless as DiMaggio and Vernon [1] suggest the print was left in a soft substrate permitting the foot to sink into the ground forming a deeper impression. It is therefore suggested by DiMaggio & Vernon [1] that footprints identified on hard surfaces would be shorter in length and width from the actual foot which left the impression. However, it is the extreme parts of the heel and toe ends which form the overall fleshed foot shape including length.

Approximating actual fleshed foot length from an unknown crime scene footprint may assist forensic examiners in building a biological profile of an individual or perpetrator present at the scene. Furthermore, this is also important if a suspect is detained in custody and comparison is performed between their foot and an unknown footprint to establish correspondence or incompatibility or further investigative leads. However, it is unclear how this approximation from footprint dimensions can be robustly performed. Currently a 'rule of thumb' approach of adding 1.5cm to 2cm to footprint length is used to approximate its true value [1], with no objective figure for forefoot width. However, this approach lacks supporting empirical evidence as it is largely based on anecdotal observations. Furthermore, no studies have explored potential variations in forefoot widths between the fleshed foot and bare footprints.

Greater understanding of the variation and significance between measurements of the fleshed foot and those of footprints is indicated to develop underpinning knowledge to support the reporting of pedal evidence in forensic investigation. This contribution to the volume of collected physical evidence may also strengthen its evidential value to assist in positively linking a suspect to a crime or to prove an individual innocent. From the literature, Barker and Scheuer [2] compared standing fleshed foot and walking footprint measurements (n=105) and found walking footprint length ($\bar{x}$=255.40mm) exceeded standing fleshed foot length ($\bar{x}$=254.20mm). However, results were exposed to measurement error from the use of a crude pen and ruler approach and it is unknown whether differences were statistically significant.

Few studies have examined bare footprint formation across different dynamic activities, such as walking or jumping. Barker and Scheuer [2] suggested that footprint morphology may vary depending on what activity is performed. Neves et al. [10] have shown that walking footprints are larger than standing footprints by an average of 17.89mm +/- 4.81mm (first ‘Great’ toe to heel length). The same was found comparing walking and running footprints, but by a smaller average difference (7.07mm +/- 7.98mm). However, this study used the Gunn method to measure footprint lengths which has not been validated regarding its repeatability. Furthermore, it was also limited to a small number of participants (n=11).

In a recent study, Bailey et al. [11] compared standing and jumping footprint measurements. Standing footprints were taken from both feet of 23 participants. This was repeated after participants jumped down from a height of 48cm. Results showed that after jumping, mean footprint length was significantly greater for both feet (p=.000) compared to standing footprint lengths. A similar increase, reported as statistically significant (p=.002) was shown when the widths of jumping footprints were compared to standing footprints. Although sample size was small, with no comparative data collected for standing fleshed foot measurement, results clearly suggest variation in footprint morphology between standing and jumping states. Variation is also acknowledged by Reel [12] who suggested an average difference of 18mm in length measurements between standing and walking footprints. In a previous study, Reel et al. [13] established a reliable and robust footprint measurement approach (n=61), using three walking and three standing footprints from each participant’s right foot. Although this was predominantly a reliability study, secondary findings showed mean footprint length measurements to be greater in walking compared to a standing state. This may be explained by the fact that Reel [12] and Reel et al. [13] measured walking footprints and included ghosting features at the heel and toe ends. Vernon et al. [14] describe ghosting as additional lighter markings at the outer edges of the heel and toe print areas, which are largely absent in standing footprints. Burrow [15] concurs suggesting that ghosting can be seen as lighter shading extending beyond areas of the footprint, which is characterised by the appearance of 'extensions' to the toe ends. It is suggested that ghosting is more likely to result from the dynamic and hence propulsive phase of gait, where the resulting bare footprint is composed of an inner weight-bearing dark impression with additional outer ghosting features at peripheral edges. Considering distinction between these areas and consistency of approach when measuring length, Burrow [15] suggests this phenomenon has implications for deciding which areas of the footprint to measure. Furthermore, Reel [16] adds that ghosting is not a stable feature, that is, it may not always appear in dynamically created footprints and that dimensions can vary.

From a literature search, no other investigations have addressed these issues with only one study investigating the cause of ghosting in dynamic footprints [14]. Although the sample in this latter study was small (n=7), with no statistical analysis of results, exploratory observations identified that the inner dark area represents the true or main footprint formed from a prolonged contact of the foot with the ground [14]. It was reported that the outer ghosting feature at the heel and toe ends corresponded with shorter periods of ground contact where the fibro fatty heel pad splayed posteriorly at initial contact, followed by the distal aspect of the toes briefly contacting the ground following heel lift. Crucially, it was reported that while the measurement of footprints with ghosting has been validated by Reel et al. [13] this has not been established for measurement of the inner dark area of bare footprints. Furthermore, Vernon et al. [14] suggests previous research has not defined which areas of the footprint have been used for measurement and data analysis. This represents a key issue for further research, with distinction between these two areas considered in context. A literature review revealed no previous studies comparing measurements across different dynamic states using the inner dark and outer ghosting areas of footprints.

Therefore, the aim of this study was to examine variation between standing fleshed foot measurement and walking and jumping footprint measurement, to develop understanding of potential differences and to the factors which may explain their existence. It is hoped this will provide forensic examiners with new insight into interpretative aspects of bare footprint analysis. As identified by DiMaggio and Vernon [1] this is of particular importance for the consideration of the implied fleshed foot size represented within crime scene footprints. Consideration is afforded to the variability in footprint morphology between different dynamic states, such as walking and jumping and to differences resulting from the inner dark areas and outer ghosting features of footprints. The latter is important in forensic practice as this will contribute to understanding of the comparative significance for the collection of additional identification points, namely, the inner dark areas to strengthen the value of bare footprint evidence in criminal justice systems.

2. Material and methods

This study followed a repeated measures design across three conditions (standing, walking and jumping) to compare differences in length and forefoot width of the fleshed foot and bare footprints. Measurements of length and forefoot width of the right fleshed foot were obtained from each participant standing in a full weight bearing position. Dynamic footprints from the right foot, that is, footprints formed from the activities of walking and jumping forward were obtained to measure length and forefoot width. Burrow [15] defines dynamic footprints as those left from walking as opposed to static footprints, which are prints left standing still with no movement. The width of the forefoot or ball of foot has been reported by Reel et al. [13] as the MPJ width (metatarsophalangeal joint width) and by Burrow [17] as the cross ball width or line. Ethics committee approval was obtained prior to the start of the study, with ethical principles of research practice followed in compliance with the Declaration of Helsinki [18].

Recruitment achieved a sample of thirteen adult, male, Caucasian participants aged 20 to 50 years with a Body Mass Index (BMI) < $30 kg/m^2$ and no history of foot trauma, deformity, pathology, surgery, gait disturbance or chronic disease influencing gait. This supports external validity to a homogenous population, as literature suggests variation in foot morphology between different ethnic groups [9,19]. All participants' heights and weights were measured using a SECA 213 Leicester Portable Stadiometer and a SECA 875 Digital Flat Scale. Sample characteristics are shown in Table 1. All participants were given information about the study to facilitate consent and were informed of their right to withdraw at any point without prejudice. Data were anonymised and stored on a password secured USB storage device ensuring protection and confidentiality.

Table 1

Sample Characteristics

	Age (years)	Weight (Kg)	Height (cm)	BMI (kg/m^2)
Mean ($\bar{x}$)	**32.23**	**82.33**	**176.79**	**26.40**
SD	**10.66**	**14.31**	**8.19**	**4.31**

BMI: Body Mass Index, SD: Standard Deviation

Only right fleshed foot and right footprint measurements were recorded ensuring consistency of approach and the independence assumption of statistical analysis [20]. A single investigator performed all procedures and measurements supporting intra-rater reliability [21]. To control for potential effects of diurnal variation in foot size, all measurements were collected between 09:00 and 12:00 [22,23]. Although Burrow [24] reported that time of day does not influence collection of footprint data, findings in this study were limited to 16 participants potentially reducing statistical power of results. Caution was advised to consider situations where environmental and temperature variations are apparent. The environment was risk assessed for any hazardous objects, prior to bare footprint collection.

2.1 Standing Fleshed Foot Measurement

Right fleshed foot length was measured on a Ward's Forensics Osteometric Board. Kanchan et al. [25] define foot length as the distance between the heel's rearmost aspect (pternion) to the longest toe (acropodion). Each participant stood with both feet in a full weight bearing position looking straight ahead and with the osteometric board under the right foot. With each participant adopting a relaxed posture with body weight evenly distributed between both feet, the right foot was checked to ensure it was in a perpendicular position relative to the fixed headpiece of the osteometric board behind the heel. The sliding metric scale of the osteometric board was then adjusted to meet the acropodion with foot length measurements recorded in millimetres (mm).

Forefoot width was measured in the same position using a Mitutoyo Digimatic Caliper (Absolute IP67, Model No: 500-754-10, Accuracy: ±0.02mm, Resolution: 0.01mm). The caliper was placed over the dorsum of the right forefoot and the most prominent margins of the 1st and 5th MPJs were located by an experienced Podiatrist. This enabled caliper alignment in the correct position to record forefoot width measurements in millimetres [26].

All equipment was cleaned between each participant using PDI Sani Cloth Duo fungicidal and bactericidal disinfectant wipes.

2.2 Walking Footprint Collection

One walking right footprint was collected from each participant using an Inkless Shoeprint Kit (TETRA Scene of Crime Ltd. Model Number: TFL0101). This was chosen as it is cost-effective and pragmatic to use compared to more technological approaches [3,13,27,28]. Its use has no reported history of allergic reaction or concerns regarding cross infection and hygiene [13].

Participant start position was marked on a hard floor with masking tape (Fig.1) Each participant was instructed to practise walking barefoot at normal pace along a six-metre walkway to familiarise themselves with the environment [29]. This permitted determination of correct placement of the inkless mat and reactive paper for footprint collection.

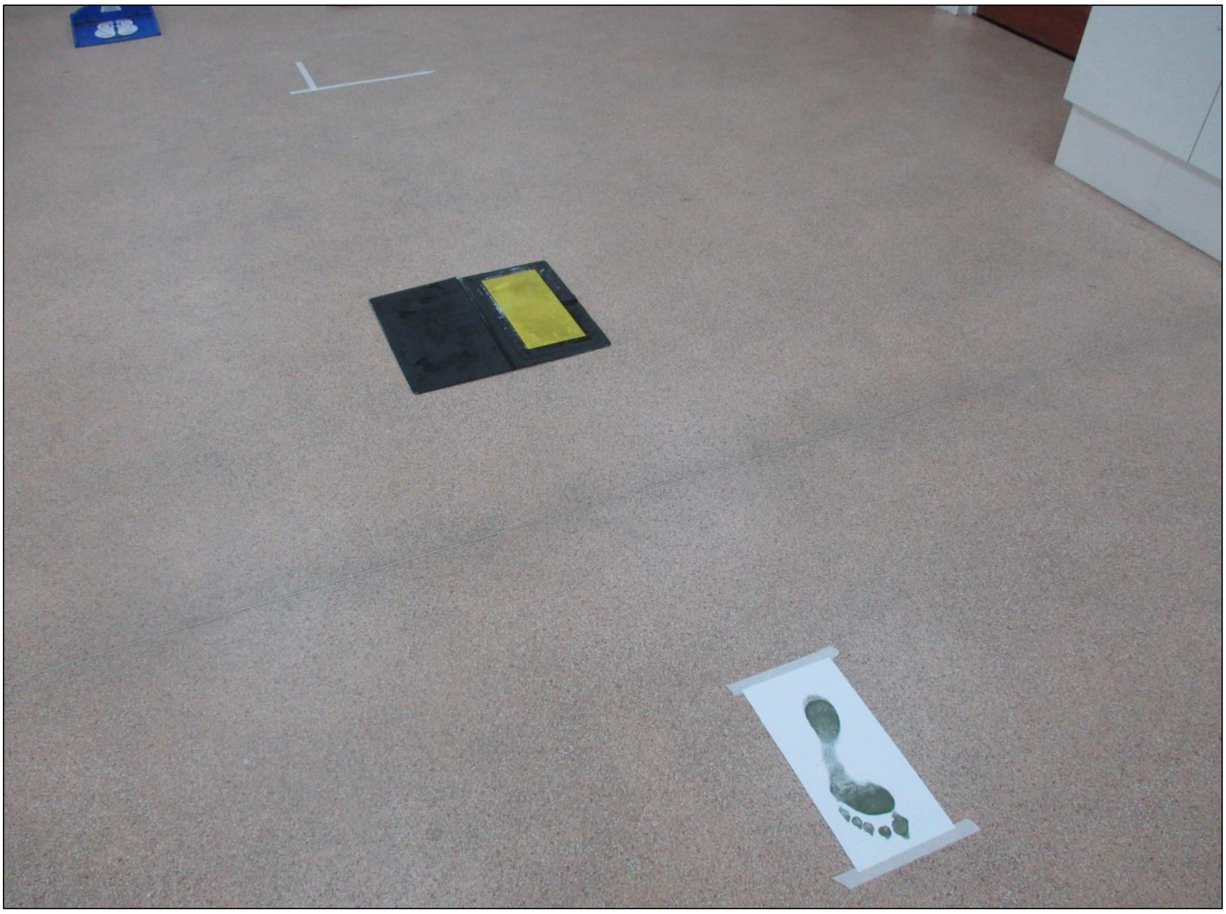

Fig 1. Inkless shoeprint kit for footprint collection showing masking tape for start position, Inkless mat and Reactive footprint paper.

Using a 5th step protocol [14,28] participants were asked to undertake their habitual walking speed to control cadence, supporting identical walking conditions [30]. A 5th step protocol was selected as this best replicates mid-gait patterns of cadence rather than a one-step approach [14]. At the start position participants were instructed to look ahead and start their first step with their right foot. The inkless mat was positioned and adjusted to capture the entire plantar surface of the third right foot step. Similarly, the reactive paper was positioned to obtain a full contact footprint of the fifth right foot step. After this fifth step, participants continued to walk forward for a further four steps.

2.3 Jumping Footprint Collection

Jumping footprints were collected using an adapted 5th step protocol, similar to that followed by Vernon et al. [14] and Reel et al. [28] for walking footprint collection. One jumping right footprint was collected from each participant under identical conditions. Participants were asked to practise jumping by leaping forward off their left foot and landing on their right foot. This supported familiarisation and correct positioning of the reactive paper to obtain a complete impression of the right footprint. Participants started their first step with their right foot, resulting in contact with inkless mat on the third step. Jumping forward then followed with take-off from the fourth left foot step with landing on the reactive paper on the fifth right foot step with continuation and push off from this point. After this landing point each participant continued forward for a further four steps.

2.4 Dynamic Footprint Measurement

The Reel method of footprint measurement [13] was used to measure footprints as it has been validated for reliability (Intra-rater reliability: Length measurement – Intraclass Correlation Coefficient (ICC): 0.99, Bland and Altman's 95% Limits of Agreement (LOA): 0.91 to 0.65, 95% confidence interval (CI): 0.28 to 0.01. Standard Error of Measurement (SEM) for intra and inter-rater reliability for length and width measurements: 0.05mm and 0.13mm). Footprints were scanned onto a Hewlett Packard computer using an EPSON Workforce WF-7610 A3 printer. An A3 printer was selected to transfer footprints onto the computer, as a large foot's length may exceed the boundaries of A4 settings. Footprints were scanned at 1200dpi and saved as TIF files. Burrow [17] recommends that files should be saved in lossless TIF formats as they will remain intact with no loss of data, particularly when they are accessed repeatedly for measurement.

All footprint images were digitally measured using GNU Image Manipulation Program (GIMP) software version 2.8.18. This was selected as Reel et al. [13] used this software to demonstrate a robust approach for measuring standing and walking footprints, which was shown to be valid and reliable. An American Board of Forensic Odontology (ABFO) Photomacrographic Scale was included in all scanned prints to support correct scaling to original size. The scale-image function in GIMP software was used to check a 10mm length and width measurement on the ABFO scale to confirm life size scaling. In cases where there was no correspondence, the scale-image function was used to ensure correct life size scaling of the image.

Using GIMP software lines were drawn from the pternion to the acropodion and across the forefoot's widest part to obtain length and width measurements in millimetres (mm) from walking and jumping footprints [13].

Two footprint length measurements were taken for the inner dark and outer ghosting areas, which included the heel and toe impressions of walking and jumping footprints (Fig.2) described in section 2.5.

Fig 2. A walking right footprint showing outer and lighter ghosting features at the furthest end of all five toes and at the rear aspect of the heel. Demarcation between the footprint's ghosting areas and inner dark regions is evident, particularly at the heel.

Considering the footprint in its entirety including the outer and lighter ghosting areas, length measurements were obtained from the most proximal and lowest pixel of the heel to the furthest and most distal pixel of the toe end [13]. Following a similar approach, the longest length of each footprint's inner dark area was measured by visually selecting and connecting the most proximal dark pixel of the heel to the most distal dark pixel of the same toe that was used for length measurements with ghosting. Burrow [15] identifies that it can be difficult to determine exact points to measure the inner dark area, as a judgement needs to be made as to the precise co-ordinates at which the dark toe impression and lighter ghost image overlap. Hence, for this study measurement points were best selected at the demarcation between the inner dark and outer lighter ghosting areas.

2.5 Measurement Accuracy

Footprints were aligned vertically using GIMP software to achieve a central axis [3]. As described by Reel et al. [13,28] this ensured consistent measurements, supporting accurate identification of the furthest pixel at the heel's base from which to draw length lines. Obtaining consistent length measurements from the same position on the heel is vital, as small variations in selection of points can result in significant differences [27]. Using the Reel method [13] the pternion was located by drawing two tangent lines; one connecting the forefoot's most lateral aspect and heel known as the outer tangent and the other repeated on the medial border of the footprint creating an inner tangent line (Fig.3). These lines were extended posterior to the heel until they bisected forming a central axis reference point. A central axis line was drawn from this point to equally bisect the footprint's full length, enabling location of the pternion from which to measure length to the acropodion. Forefoot width measurements were measured between the outer and inner tangent lines corresponding to the most lateral and medial points of the 1st and 5th MPJs [3,26,27,28,31,32].

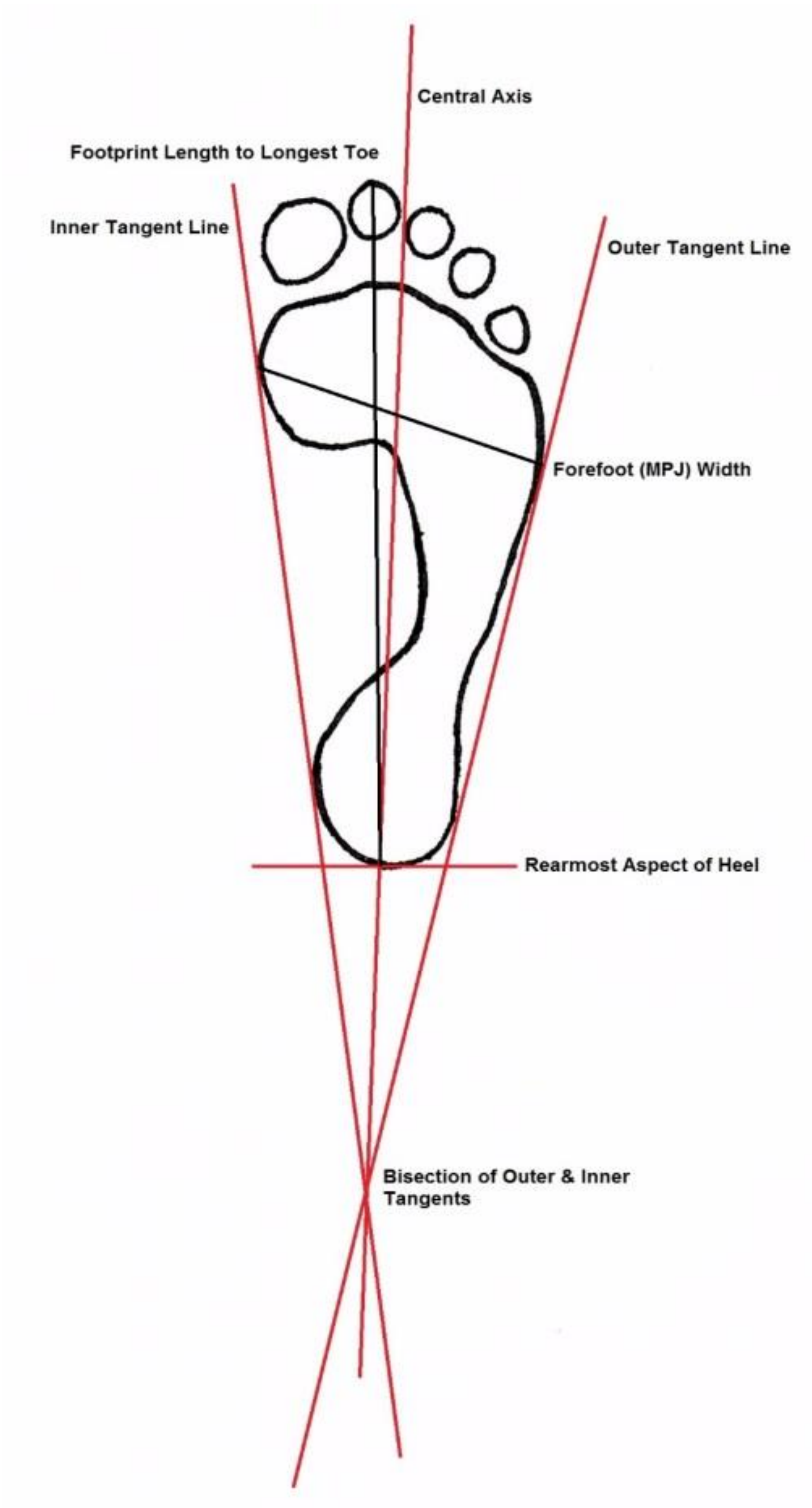

Fig 3. Footprint length & width measurements (Reel et al., 2010)

2.6 Descriptive Statistical Analysis

Statistical Package for the Social Sciences (SPSS) version 22.0 was used to investigate mean differences between measurements. Univariate analysis was undertaken for standing, walking and jumping measurements examining central tendency (mean values), standard error of mean (SE) and spread of distribution about the mean (range and standard deviation). Boxplots show comparative data for length and width measurements between all independent variables. For the purposes of data analysis, the inner dark prints were expressed as ‘footprints without ghosting’ (non-ghosting) and those with ghosting were referred to as ‘footprints with ghosting’ (ghost).

3. Results

Table 1 shows sample characteristics. Descriptive statistics for standing fleshed foot and walking and jumping footprint length measurements are shown in Table 2. Forefoot width measurements are shown in Table 3. No data outliers were found.

3.1 Comparison of Fleshed Foot & Footprint Lengths

Walking footprint length with ghosting ($\bar{x}$=268.61mm) was greater than standing fleshed foot length ($\bar{x}$=264.30mm). Participant 11 showed no footprint ghosting from walking, hence, no data was available from this participant to be included in the comparison against standing fleshed foot length. This is acknowledged by Reel [16] who identifies that ghosting is not a stable feature and Burrow [15] who reported that ghosting does not occur repeatedly even for the same participant.

In contrast, standing fleshed foot length ($\bar{x}$=264.30mm) was greater when compared to walking footprint length without ghosting ($\bar{x}$=254.85mm). Data in Figures 4 and 5 reiterate this finding.

The standard error of mean (SE) for all length measurements was high due to the small sample size. Considering measures of variability within the dataset, the smallest range (Table 2) is reported for standing fleshed foot length (57.00mm), compared to walking (61.00mm) and jumping (59.80mm) footprint lengths with ghosting.

Table 2

Descriptive Statistics for Fleshed Foot & Footprint Length Measurements

Activity	N	$\bar{x}$	SE	Range	Maximum	Minimum	SD
Standing Foot	13	264.30	4.67	57.00	297.00	240.00	16.85
Walk Footprint (Ghosting)	12	268.61	5.30	61.00	302.00	241.00	18.39
Walk Footprint (Non-Ghosting)	13	254.85	4.44	53.20	286.80	233.60	16.01
Jump Footprint (Ghosting)	11	261.57	5.98	59.80	298.30	238.50	19.86
Jump Footprint (Non-Ghosting)	13	255.63	4.55	53.60	287.00	233.40	16.41

Values in millimetres (mm), Number of Participants = N, Mean = $\bar{x}$ *, Standard Error of Mean = SE, Standard Deviation = SD*

Standing fleshed foot length ($\bar{x}$=264.30mm) was greater than jumping footprint length with ghosting ($\bar{x}$=261.57mm). Participants 6 and 9 showed no footprint ghosting from jumping, which resulted in a smaller number of participants for comparison. As highlighted the stability and occurrence of ghosting is not an assured feature in bare footprint formation from walking [15,16]. However, it is not known why participants 6 and 9 did not show ghosting in their footprints after undertaking a forward jump, considering this is a different dynamic activity to walking.

There was a greater range of measurement (59.80mm), larger interquartile range (IQR) and higher standard deviation (SD) (19.86) for jumping footprint length with ghosting, compared to standing fleshed foot length (Table 2 and Fig. 4).

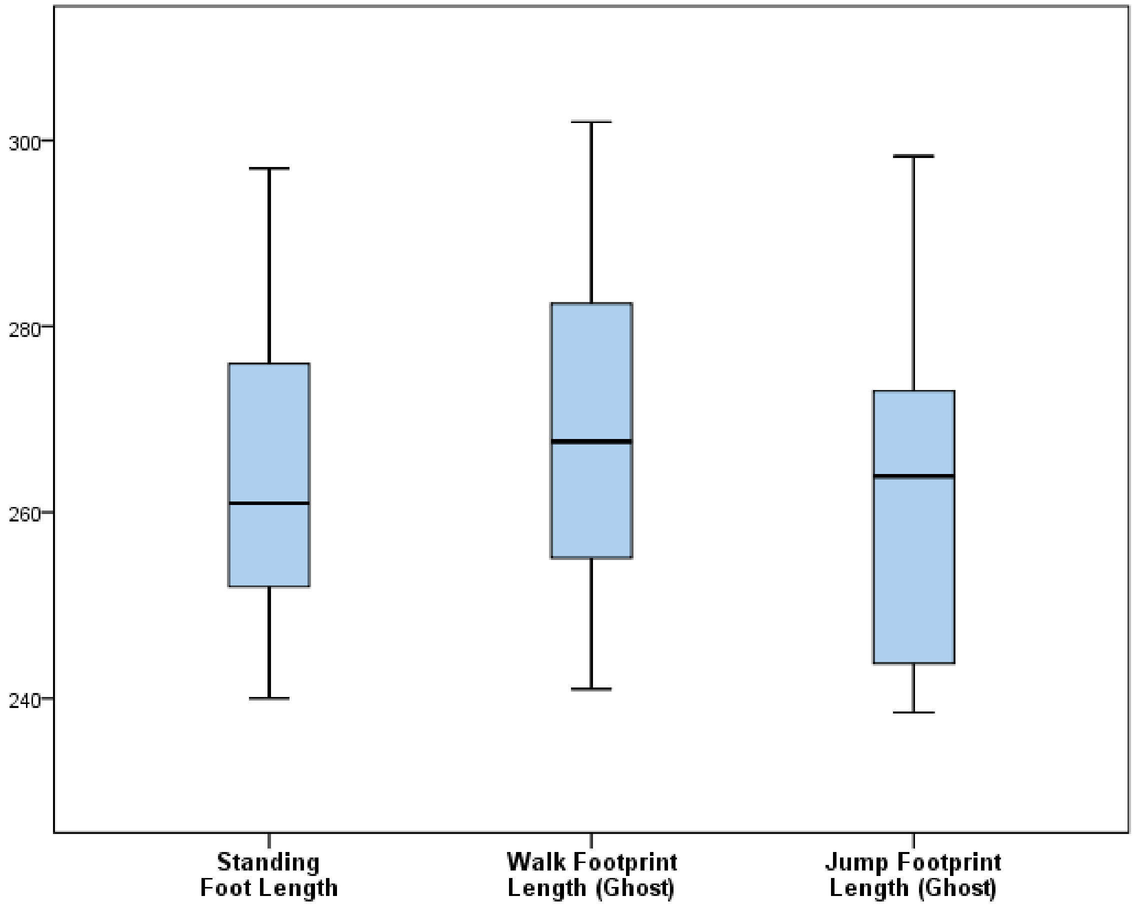
300
280
260
240
Standing Foot Length
Walk Footprint Length (Ghost)
Jump Footprint Length (Ghost)

Fig 4. Boxplot comparing standing foot length and walking and jumping footprint lengths with ghosting in millimetres (mm)

When standing fleshed foot length was compared to jumping footprint length without ghosting ($\bar{x}$=255.63mm), analysis showed it was greater. Standing fleshed foot length also showed the greatest range in measurements (57.00mm) compared to walking (53.20mm) and jumping (53.60mm) footprint lengths without ghosting.

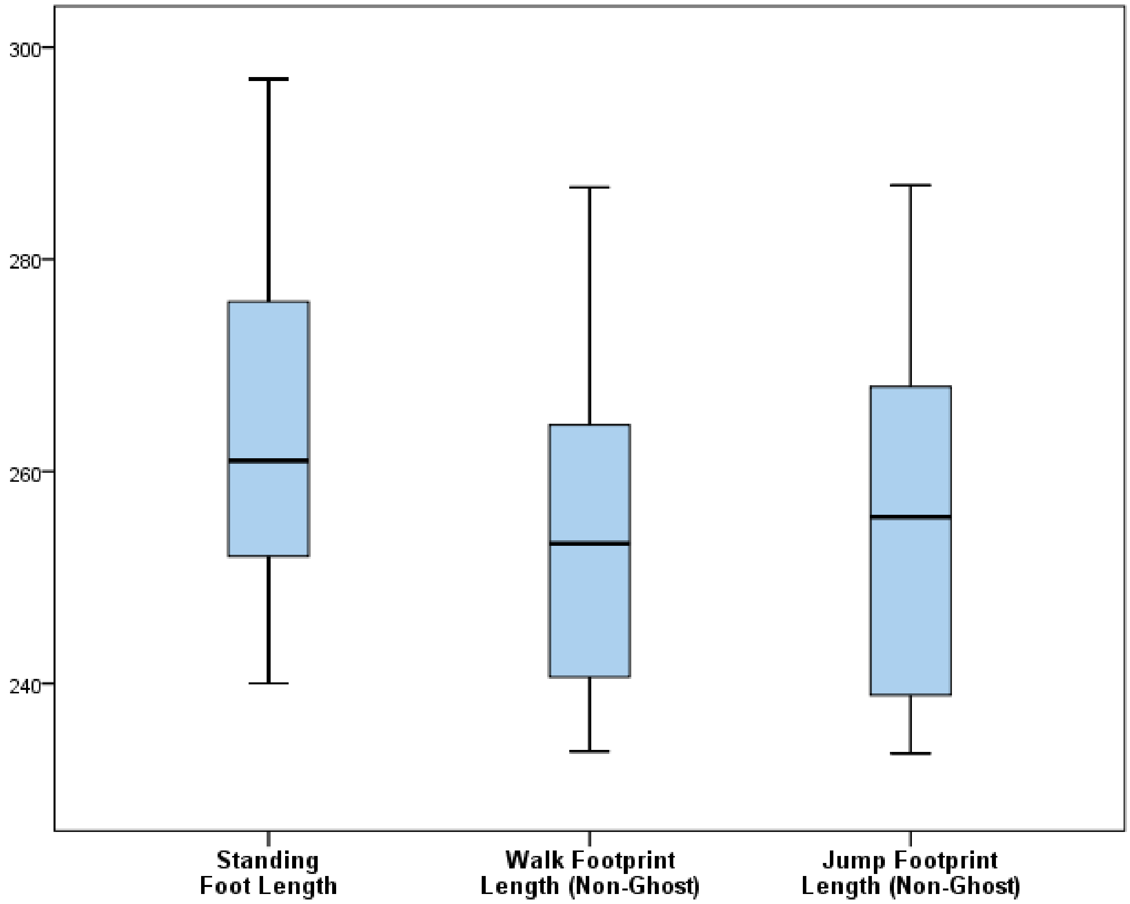

Fig 5. Boxplot comparing standing foot length and walking and jumping footprint lengths without ghosting in millimetres (mm)

3.2 Comparison of Walking & Jumping Footprint Lengths

Walking footprint length with ghosting ($\bar{x}$=268.61mm) was greater than jumping footprint length with ghosting ($\bar{x}$=261.57mm). It is acknowledged that a ghosting phenomenon was not evident in the walking footprint of participant 11 and also in jumping footprints of participants 6 and 9. However, from comparison of this data the difference between these two dynamic states was 7.04mm.

When the inner dark areas (non-ghosting) of the footprints were compared, results show that jumping footprint length ($\bar{x}$=255.63mm) was greater than walking footprint length ($\bar{x}$=254.85mm), however, the difference was smaller (0.78mm).

3.3 Comparison of Inner Dark & Outer Ghosting Footprint Lengths

When the inner dark footprint length measurements and the outer ghosting footprint length measurements were compared within each dynamic state, that is, in walking and in jumping activities respectively the mean variation between these measurements was 13.76mm in walking and 5.94mm in jumping.

3.4 Comparison of Fleshed Foot & Footprint Widths

Table 3 shows standing forefoot width ($\bar{x}$=105.06mm) was greater than jumping footprint width ($\bar{x}$=98.03mm) and walking footprint width ($\bar{x}$=95.63mm). This is evident at median points in Figure 6.

Table 3

Descriptive Statistics for Fleshed Foot & Footprint Width Measurements

Activity	N	$\bar{x}$	SE	Range	Maximum	Minimum	SD
Standing Foot	13	105.06	1.38	16.90	112.70	95.80	5.00
Walk Footprint	13	95.63	1.23	13.60	101.70	88.10	4.45
Jump Footprint	13	98.03	1.53	18.60	107.60	89.00	5.52

Values in millimetres (mm), Number of Participants = N, Mean = $\bar{x}$, Standard Error of Mean = SE, Standard Deviation = SD

Results also show jumping footprint width ($\bar{x}$=98.03mm) was greater than walking footprint width ($\bar{x}$=95.63mm). Figure 6 and Table 3 also show jumping footprint width demonstrates the greatest range (18.60mm), compared to standing forefoot width (16.90mm) and walking footprint width (13.60mm). Standard deviations between all three independent variables are similar (Table 3).

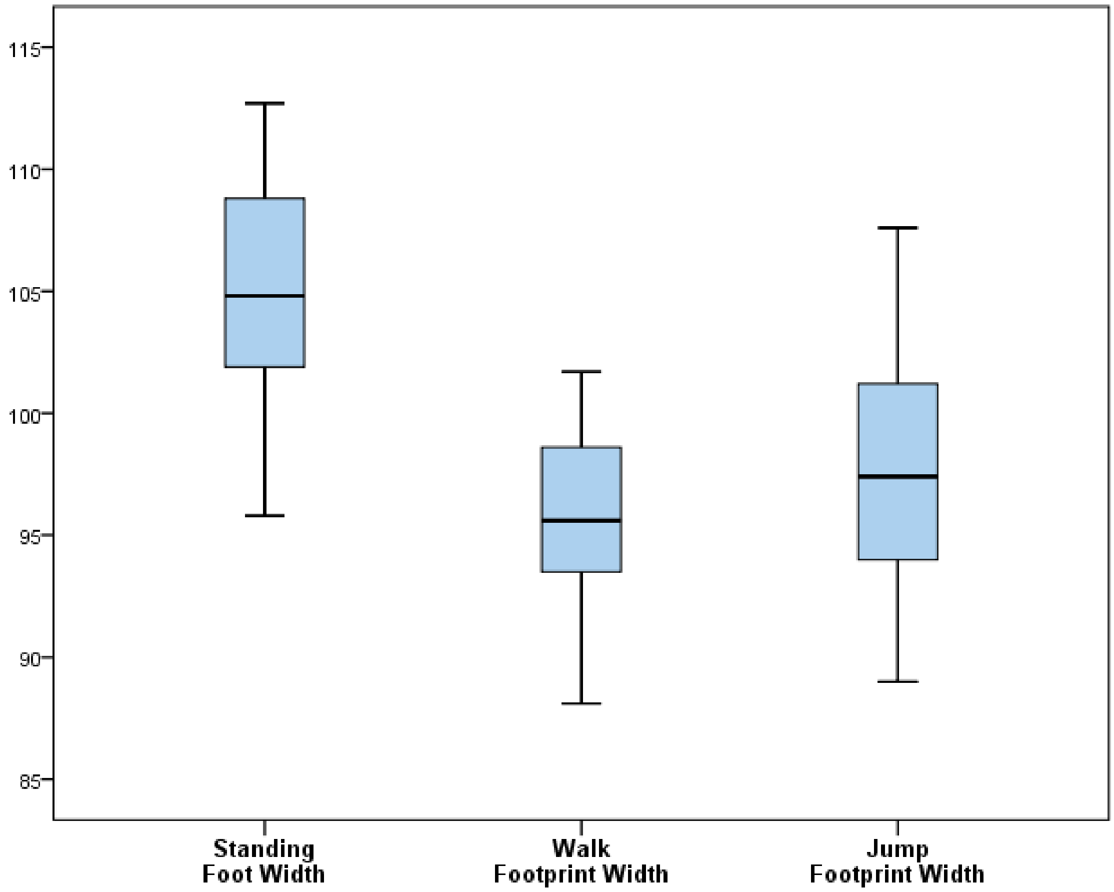

Fig 6. Boxplot comparing forefoot width measurements in millimetres (mm) of the standing foot and walking and jumping footprints

4. Discussion

This study used a pragmatic approach to measure participants' right feet in a standing full weight bearing position and to capture walking and jumping bare footprints using the same foot. Walking and jumping footprints were measured with results compared to those of the standing fleshed foot. A secondary analysis compared walking and jumping footprints, including differences between the inner dark and outer ghosting areas within each dynamic activity of walking and jumping. In this analysis ghosting was considered as a combination of the phenomenon at the end of the toes and at the rear aspect of the heel.

Findings from this study support those of Barker and Scheuer [2] who reported walking footprint length ($\bar{x}$=255.4mm, SD=18.4, n=105) to be greater than standing fleshed foot length ($\bar{x}$=254.2mm, SD=17.0, n=105). The magnitude of this difference was small (1.2mm), compared to our investigation which found a 4.31mm difference. However, this is only in agreement when walking footprint lengths with ghosting are compared. Barker and Scheuer [2] did not distinguish between inner dark and outer ghosting areas; a factor acknowledged by Vernon et al. [14]. Our findings do not dispute the inference by Barker and Scheuer [2] that this length difference is attributable to the foot elongating during the stance phase of gait where loading is accepted by the foot from vertical forces of bodyweight which then act along its lateral plantar border, passing medially across the ball of foot to toe off. Although our study did not compare standing footprint measurements, Reel et al. [13] reported a similar finding where footprint lengths were shown to be greater in walking compared to a standing state. This was also reported by Neves et al. [10] who found walking and running footprint lengths to be larger than standing footprint lengths. However, foot elongation may not fully explain this difference, as Vernon et al. [14] suggests ghosting in dynamic footprints may contribute to greater length measurements resulting from the backward splaying of the heel's fibro-fatty pad and from curvature of the toe apices rolling off the supporting surface.

Conversely findings from our study show that when the inner dark area of the walking footprint is considered, its length was shorter than standing fleshed foot length. This agrees with the suggestion offered by DiMaggio and Vernon [1] that footprints identified on hard surfaces are shorter in length from the foot which left the impression. However, this inference may only be applicable to length measurements obtained from the inner dark area of footprints and to those formed in a standing position. Therefore, the approach of adding 1.5cm to 2cm to footprint length to approximate its true fleshed foot length is questionable, as it may be difficult to clearly differentiate between the inner dark and outer ghosting areas of crime scene footprints. This is acknowledged by Burrow [15] who identified difficulties in determining where the actual toe impression and ghost feature overlapped. Furthermore, it may be difficult to discern whether a crime scene footprint was formed from a dynamic activity or a standing position, particularly where substrates which the foot has impacted on are variable. In addition, applying this approach to walking footprint lengths with ghosting may also be erroneous because of the reported shorter standing fleshed foot length found in our study. It is also postulated that the maximum length of the inner dark area of walking footprints (without ghosting) may be similar in morphology to standing footprint lengths, as they both do not involve the component of foot length where the heel and toe ends curve dorsally. Further investigation would be needed to provide conclusive answers.

Considering differences in footprint length between walking and jumping activities inclusive of ghosting at heel and toe ends, results showed that walking footprint length ($\bar{x}$=268.61mm) was greater than jumping footprint length ($\bar{x}$=261.57mm). In a recent study of footprint lengths collected from jumping, Bailey et al. [11] reported from a sample of 23 participants that mean jumping footprint length for the right foot was 245.87mm. This is notably different to our findings resulting in a comparative difference of 15.70mm. This variation may be explained by the fact that the type of jumping activity was different between studies. Bailey et al. [11] investigated jumping down from a step of fixed height (48cm), whereas our study looked at footprints jumping forward in a leaping motion from a walking start point. This difference may go some way to explaining how much or how little the foot elongates between different activities. Further studies are required to determine the formation and dimension of footprints across different types of jumping activity, such as jumping up onto a stair, over an obstacle or down from varying heights. This is acknowledged by Bailey et al. [11] who suggested further investigation using additional variables including different heights and types of landing surface, such as carpet and concrete. It is also important to appreciate that Bailey et al. [11] only collected footprint length measurements inclusive of ghosting and it is unknown whether results could have differed if the inner dark areas of the footprints were considered.

When the difference between the inner dark and outer ghosting areas are considered from our study within each dynamic state, that is walking or jumping, results show a mean difference of 13.76mm in walking footprints with a smaller 5.94mm in jumping footprints. These values reflect the total mean size of footprint ghosting by considering the difference between the total length of the footprints inner dark area and the total length of footprints inclusive of ghosting at both heel and toe ends. It is interesting to note that findings reported by Burrow [15] used an illustration of a partial footprint (figure 2) to compare ghost images in all five toes of a walking footprint and that the size of ghosting decreased sequentially from the first ‘Great’ toe print (0.96cm / 9.60mm) to the fifth ‘smallest’ toe print (0.288cm / 2.88mm). Although Burrow [15] did not measure jumping footprints and omitted to consider ghosting at the heel, it is worth considering these descriptive measures in relation to the smaller value of 5.94mm in jumping footprints from our study. In conjunction with other variable factors, such as type of collection method, foot structure, range of motion at articular joints and angle and base of gait, the size of ghosting may be dependent on the type of dynamic activity undertaken. Further to this, it is postulated that differences in the size of ghosting between walking and jumping activities in our study may result from variations in the magnitude and direction of force vectors affecting footprint formation.

Furthermore, during jumping, the foot on landing may experience a smaller duration of loading with shorter elongation of its length compared to walking. This may be because of rapid movement of the body's centre of gravity (COG) in a vertical direction. Although Vernon et al. [14] reported an association with ghosting and foot elongation, including the suggestion that the inner dark area corresponded with the region of the toes which had the greatest duration of ground contact, this was only for walking footprints. When Burrow [15] examined ghosting in walking footprints, it was reported that this phenomenon appears at the end of the toes as a lighter image in addition to the main footprint. However, the main footprint is not defined and it is assumed this is the inner dark area of the footprint. Findings also not only showed ghosting at the end of all five toes in a number of participants, but in some cases this was missing particularly at the end of the 5th toe print. Furthermore, it was found that in some footprints the entire 5th toe print was missing. The latter anomaly is also reported by Reel et al. [28] in collection of standing footprints. Reel et al. [28] postulated that if bodyweight is directed more distally over the feet rather than the heel region, this may cause the peripheral nerves which innervate the intrinsic extensor muscles of the toes to fire prematurely in preparation for gait, thereby resulting in the extensor tendons of the lesser toes contracting prior to toe-off and propulsion. Furthermore, it is suggested by Reel et al. [28] that the extensor tendons to the lesser toes are weaker compared to the first 'Great' toe, which has greater stability from its stronger extensor and flexor tendons around the interphalangeal joint. This weakness suggests that the lesser toes, particularly the smallest 5th toe, are more likely to exhibit laxity in their range of motion increasing the likelihood of absent toe prints. This appears plausible and although Burrow [15] did not consider ghosting at the rearmost aspect of the heel, results indicate that ghosting is a random and intermittent feature, requiring further investigation to understand the reasons why it does not appear in all dynamically created footprints.

Duration of ground contact and foot elongation may vary depending on the type and speed of dynamic activity undertaken. If the foot on landing from a jump is in contact with the ground for a shorter duration, it may not elongate to its full range when vertical ground reaction forces (GRF) are attenuated, as the foot needs to rapidly supinate to lock its structure into a rigid lever for propulsion and push off. These reductions in contact time may decrease the magnitude and size of ghosting, corresponding to shorter footprint lengths. Conversely, factors relating to foot structure may have a part to play in the formation of ghosting. For example, a mobile foot with laxity in ligamentous and tendinous structures may display a greater degree of ghosting in dynamically created footprints compared to a foot that is less mobile and more rigid.

Equally when jumping forward, the heel of the landing foot may not achieve full ground contact as momentum may cause the forefoot's plantar metatarsal area, that is, the ball of foot to experience a greater degree of the loading especially if the jump is quickly carried through into the next phase of motion. This may explain why jumping footprint width was greater than walking footprint width, where the magnitude of forefoot spread on ground contact is larger compared to walking. This concurs with Bailey et al. [11] who not only reported increases in footprint length, but also in width resulting from perceived forces passing through a jumping footprint exceeding those through a walking footprint which in turn exceeds those through a standing footprint. Further work is indicated to investigate these effects under varying dynamic states.

Although our results agree with those reported by Barker and Scheuer [2] it must be considered there were differences in design. Barker and Scheuer [2] used a mixed sample of male and female participants, compared to males in our study. This may explain why mean walking footprint length (255.4mm) was smaller, compared to our study (268.61mm), as females have predominantly smaller feet [7,33]. Similar issues also affect findings reported by Neves et al. [10] as their sample was composed of six male and five female participants.

Furthermore, differences in footprint collection methods are evident which may explain these variations. Barker and Scheuer [2] used water-soluble poster paint to create footprint impressions on paper, whereas, our study used the Inkless

Shoeprint Kit system. Importantly, Barker and Scheuer [2] reported characteristic smudging in the heel strike and toe off areas of footprints, which may be explained by the foot 'sliding' on the paper due to the wet paint. Therefore, differences in footprint collection methods may be a significant factor as Burrow [15] reported that ghosting was more prevalent in footprints collected using the Podotrack System, compared to those collected with the Inkless System. In addition, this variation may be explained by the fact that in our study participant 13 had a UK shoe size 14, corresponding to a large right foot. This may have skewed our results compared to Barker and Scheuer, however, what is not known is the size of participants' feet and/or shoes in the sample used by Barker and Scheuer compared to our sample.

It is unclear why Barker and Scheuer [2] did not publish all descriptive statistics for males and females separately, as they reported mean fleshed foot length for males to be 264.93mm (SD=14.02), which is similar to our study ($\bar{x}$=264.30mm, SD=16.85). Barker and Scheuer [2] also used a larger sample (n=105), but it is unclear why inferential analysis was not undertaken with a sample of this size to identify if differences were statistically significant. The authors also limited reporting to only the left foot when considering mean fleshed foot and footprint lengths, weakening comparison with right foot measurements in our study. This is a confounding factor as Burrow [17,34] suggests that asymmetric differences between measurements of the left and right foot may be forensically significant.

Considering forefoot width measurements, results showed standing forefoot width was greater than walking or jumping footprint widths. This agrees with DiMaggio and Vernon [1] who suggested hard surface footprints can appear not as wide as the foot responsible for the impression due to extreme aspects of forefoot width not contributing to print formation. Forefoot width may also be a more stable measure as standard error of mean and standard deviation for all three independent variables was small (Table 3).

This study also found that ghosting was not present in any dynamic footprint widths, indicating it may be exclusive to sagittal plane motion. What has not been explored is whether ghosting could result along lateral or medial borders of the foot when dynamic motion occurs predominantly in the coronal (frontal) plane, for example, jumping out in a sideways movement to avoid an obstacle. Conversely, its absence may be due to a thinner density of tissue on lateral and medial borders of the forefoot resulting in limited splaying compared to the heel and toe pulp ends. It is unknown whether this phenomenon could result in humans with a high density of fibro fatty tissue along lateral and medial borders. Furthermore, it is unknown whether ghosting could manifest at footprint borders in other populations, as our study was restricted to a Caucasian population, supporting external validity to a homogenous population. Additional investigations are required to explore these in other populations.

Results also showed the length and width of standing fleshed foot measurements were greater when compared to the same measures across jumping footprints, with and without ghosting. This difference may be due to the curved anatomical shape of the foot at heel and toe ends contributing to standing fleshed foot measurements, but not to footprint formation in their complete entirety. These factors are identified by DiMaggio and Vernon [1] relating to interpretative aspects of the variation between overall fleshed foot length versus overall bare footprint length.

Despite consideration given to the distinction between inner dark and outer ghosting areas in walking and jumping footprints, there were some limitations in the design of our study. The sample size (n=13) was too small for inferential analysis. More definitive answers could be provided in much larger cohort studies, where sample size calculation could provide better estimations to investigate statistical significance between standing fleshed foot and walking and jumping footprint measurements. This is inferred by Burrow [15] who stated that a sample size of 35 participants was an appropriate number to investigate ghosting in walking bare footprints. In this study a power calculation showed that greater numbers would not have increased the confidence level.

It was also noted that ghosting did not appear in all walking and jumping footprints, reducing the size of the sample for descriptive analysis. Participants 6 and 9 showed no ghosting in jumping footprints, whilst a similar absence prevailed in the walking footprint of participant 11. This observation agrees with Reel's [16] suggestion that ghosting is not a stable feature, not always appearing in footprints created from dynamic activities such as walking or jumping. Absence of ghosting at toe pulp ends in walking footprints was also reported by Burrow [15] who, as previously stated, found that in some cases ghosting failed to occur repeatedly even for the same participant. Although Burrow [15] reported that ghosting appears more frequently at the great toe end, diminishing in its extent as the print moves laterally to the fifth toe, its stability is questionable and additional investigation is indicated to establish the extent of this anomaly in dynamically created footprints. It is acknowledged that in our study a total of two dynamic footprints were collected from each participant’s right foot, that is, one from walking and one from jumping. Because of the inconsistencies identified by Burrow [15] as to how often ghosting occurs, design could have been strengthened by collecting more than one footprint at each dynamic stage thereby improving support for ‘real world’ conditions. This is acknowledged by Reel et al. [13] who collected three standing and three walking footprints from each participant.

Furthermore, the method used in our study for standing fleshed foot measurement was not validated. Grid lines could have been added to the osteometric board to ensure repeatable perpendicular foot positioning. In addition, although a 5th step protocol for walking footprint collection [14,28] was used, this has not been validated for capturing jumping footprints. Confirming a reliable method using the Inkless Shoeprint System would have ensured content validity. This study was also performed under controlled conditions not truly representative of the ‘real world’. Vernon [35] suggests bare footprints collected under standardized conditions weaken transferability to the real world, as those found at crime scenes are subject to effects of numerous variables, such as, slippage and alternative foot function. Surfaces may be highly variable, causing changes in balance, COG and foot placement thereby influencing footprint formation. Vernon [35] highlights the point that these variable effects need to be investigated to understand their role in footprint formation.

5. Conclusions

Using descriptive analysis this study found differences between measurements of standing fleshed foot length and width and walking and jumping footprint length and width. Distinction was afforded to differences in length between and within walking and jumping states, specifically the inner dark and outer ghosting areas of footprints. These differences offer useful insight into the variability in footprint formation and morphology between different dynamic states and how these compare to standing fleshed foot measurements.

Further investigation is needed to examine if these differences are statistically significant using appropriate sample size calculation and inferential analysis. This will provide further understanding of how crime scene footprints can be interpreted to support their evidential value in criminal justice systems.

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