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REVIEW

Examination and Interpretation of Bare Footprints in Forensic Investigations

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Abstract: While there has been interest in the use of bare footprints in forensic investigations, it is only in recent times that this field has become more established through research and subsequent practice. The work of a footprint examiner is to analyze, compare and evaluate footprint evidence that has been linked to a crime scene, in the form of either bare, socked or insole foot marks. The work is often, although not exclusively, carried out by forensic podiatrists. This review outlines the methods for forensically examining two-dimensional footprint evidence, validated by underpinning research, and provides a critique of such. It also provides an overview of past influences, present policy guiding quality frameworks and recommendations for further research in forensic footprint examination.

Keywords: bare footprints, socked footprints, footprint measurement, forensic podiatry, footprint evidence, foot marks

Introduction

The human footprint is a natural consequence of bipedal ambulation and stance and is the mark left when the foot contacts the surface upon which a person has trodden – either when ambulating creating a dynamic footprint, or standing to create a static footprint. It is important to state the term "footprint" in this review refers to both bare and socked forms, unless specifically stated. It does not refer to "shoe print". The form of the footprint will vary according to whether the foot has been shod leaving a mark or impression of the foot on the insole, or unshod leaving such a mark or impression on the surface which has been contacted by the foot. The form of unshod footprints (bare or socked) will depend on whether the person has stood or ambulated over a soft surface (where the foot has sunk or partially sunk into the soft materials with which it has made contact to create a three-dimensional foot impression), or whether the contacting surface has been hard and has allowed a two-dimensional footprint to be formed.

At a crime scene, footprints have the potential to leave behind forensic evidence in the form of marks or impressions on the contact surface, the placing and dimensions of which can be considered in terms of the overall shape, or morphology.[1,2] A bare footprint can also show features from the skin of the plantar surface of the foot, namely papillary ridge detail and crease marks[3,4] and in these cases, a ridge pattern analyst would use this type of detail to demonstrate individuality to either establish or exclude associations with the postulated owner of that footprint.[5–7]

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Determination of the individuality of the human footprint shape for forensic identification purposes has been the subject of many studies[8–15] and whilst research in this area has indicated that footprint shape may be highly individual or even possibly unique, this is not certain. For example, Kennedy et al suggested a statistical probability of a 1 in 1.27 billion chance match between two independent footprints sharing the same morphological features.[14] However, it is not clear if the calculation was based on the measurements of all the footprints included in the study database of 24,000 footprints, or whether the smaller heterogeneous sample of 134 footprints investigated primarily for footprint inter-variation, was used for the statistical analysis which led to this suggestion. Whilst the statistical inference of the uniqueness of footprint morphology is disputed, it can nevertheless be argued that a combination of intermediate class-level characteristics visible in the shapes of the marks that make a footprint can represent high levels of individuality.[5]

Aside from ridge detail analysts, other disciplines and professional groups have knowledge that can be of use in considering individuality expressed by a footprint in the context of forensic identification and investigation work. While the knowledge base of such groups can overlap, each distinct group brings a slightly different perspective to the examination and interpretation of footprints to aid forensic investigations. Forensic podiatrists have taken a strong interest in this area, bringing with them their knowledge of the human foot and its anatomy, and how pathologies and the dynamics of a functioning foot can alter the form of a footprint.[3,16–19] Forensic physical examiners bring an expertise in the examination and physical comparison of marks left on a surface with the object that has created these marks, such as tool marks and tire marks.[20,21] Forensic anthropologists understand the skeletal anatomy of the human body including the bones of the foot in a forensic context and how a footprint can be compared to a foot from an anatomical perspective.[22–24]

There has been a relatively long history of the use of footprints in forensic identification and investigation work with varying degrees of success. The appreciation of a footprint as a general feature, individual to humans has been apparent for many years. For example, in his 1719 novel "The Life and Adventures of Robinson Crusoe", Defoe used the presence of a bare footprint and the recognition of its more obvious features to show the incontrovertible presence of another human on the isolated protagonist's island.[24] Generations of footprint trackers have been noted in several cultures including Khojis in the Indian subcontinent,[25] San trackers in Southern Africa,[26] Native American trackers in North America[27] and Aboriginal trackers in Australia,[28] with some possessing skills to apparently identify a person from their footprints.

In 1920, Gerard wrote a speculative article in which he considered how sequences of footprints and shoeprints could be used to associate the person who had created them.[29] These broad appreciations eventually led to the possibility of footprints being of potential use in forensic human identification. Some of the earlier published work on the use of footprints in forensic cases came out of India where a significant number of the general population are unshod.[30,31] In the western world, early publications were produced by a physical anthropologist Dr Louise Robbins[32] in relation to an investigation of prehistoric footprints that had been recently discovered by Leakey in the US.[33] Robbins continued to publish studies she had undertaken on footprints and also general information on the potential use of footprints in forensic investigations,[34–36] writing a significant textbook summarising her perspective as a forensic anthropologist working in this field.[10] Publications also emerged from other disciplines which had an interest in the use of footprints in forensic case work, particularly from podiatrists and forensic marks examiners. In the 1980s and early 1990s, Dr Norman Gunn, a Canadian podiatrist and pioneer in the field of forensic podiatry published papers showing the methods he had developed for footprint comparison.[37] Also, in Canada, the aforementioned Robert Kennedy of the Royal Canadian Mounted Police described his involvement as an expert witness in a footprint case in New Brunswick in 1989,[13] whilst William Bodziak of the Federal Bureau of Investigation discussed several crimes involving footprint evidence around the same period of time.[38]

With the emergence of such publications, the use of footprints in forensic investigations began to increase. In Canada, the increasing footprint case work of Gunn[37,39] and Kennedy[40] was reported. Similarly, in the UK, cases involving footprints were also described in the literature.[17,41] In the US, case studies involving footprints were presented at conferences, and in various journals and textbooks.[42] Among these various reported cases were those in which Robbins had been involved. In the mid-1980s, Robbins' work on footprints (as well as in the other related area of identification using the wear features of footwear) was shown to be highly problematic and

Robbins was subsequently discredited.[43–45] The associated controversy was widely publicised[46–48] and as a result, scepticism of the value of the use of footprints as an aid to forensic human identification began, particularly where such work was not being undertaken by mainstream forensic practitioners.[49]

In more recent times, in response to demands from influential review publications,[50,51] standards of forensic science and practice have been widely enhanced nationally and internationally.[52–54] For example, those continuing to work in the area of footprints have been involved in research to consider and test their value in forensic human identification including the validity and reliability of analytical methods. This is a key facet required to support both the strength and credibility of expert witness testimonies within courts of law. In the UK, Reel considered the validity and intra- and inter-rater reliability of the various methods of footprint comparison and through this suggested a new tool for such comparisons.[18,55] Testing the value of footprints in identification necessitates research to understand footprint variation within and between people under different conditions. To this end, differences have been established between standing and walking inked bare footprints collected under controlled conditions with males reported to have a mean intra-variation of 18 mm for the first toe to heel measurement.[55,56] Neves et al[56] found that running footprints were larger than static footprints but smaller than walking footprints. In a pilot study, Nirenberg et al[57] determined that there were no significant statistical differences between socked footprints and inked bare footprints, and also between insole foot marks and inked bare footprints.[58] In other examples, Howsam and Bridgen[59] investigated measurements between standing fleshed feet and walking and jumping footprints, reporting differences in lengths and widths between static and dynamic states. Differences were also found in footprint lengths between walking and jumping states. In a small-scale study, Curran et al reported differences between an inked bare footprint and a carpet footprint impression, however, a limitation of this study highlighted that all carpet footprint impressions were captured with the footprint-collecting paper placed over the carpet, rather than directly, introducing an additional variable through this method of collection.[60] Hammer et al demonstrated that whilst inked bare footprints showed similarities with their associated insole foot marks, a higher degree of similarity was observed between the insole foot marks of the same wearer and thus recommended a like-with-like process for insole comparisons.[61] However, in a small case study, Reidy found dynamic inked bare footprints were comparable to insole foot marks.[62] Where footprint measurement research has included both left and right feet, asymmetry has been noted in most publications.[23,56,63–68] Burrow noted in a limited study of sixteen participants, where four footprints were collected from each subject, that there were no significant differences in footprint size and shape between those collected in the morning and those collected in the afternoon.[69] These results have implications for forensic practice as they suggest that the timing of reference print collection can be flexible during forensic practice.

In terms of intelligence gathering, footprint research has suggested that it is possible to estimate the height of a person through their footprint length with varying measurement error estimates.[63,65,66,70–72] Krishan[73] and other authors[36,66,74,75] have suggested correlations with footprint measurements and weight, but the accuracy of the predictions is dependent on population-specific samples and is not generalizable. Additionally, work has been carried out to determine an individual's sex from a footprint[64,76–78] and a project at Bournemouth University in the UK is currently investigating the benefits of machine learning to aid the determination of sex. Fleshed foot size and thus shoe size estimation from footprint length can also be an aid for intelligence-gathering purposes and a recent study has presented a regression equation for calculating foot size from static footprint length with a prediction interval of 8 mm.[79]

The Examination of Footprints in Forensic Investigations

An examiner who is an expert in the assessment of footprints in the context of forensic investigations would follow the broad ACE-V (Assessment and Analysis, Comparison, Evaluation, Verification) process devised to guide approaches to forensic identification in many different disciplines, including fingerprint, handwriting, tool mark and footwear mark comparison.[80] Typically, a crime scene investigator would note the presence of a footprint at a crime scene and a suspect would later be found by a law enforcement agency. In the absence of ridge pattern detail, an expert in footprint analysis would be consulted as required.

The footprint evidence recovered from a crime scene is referred to as "questioned" footprints, and would first be assessed by a preliminary footprint examiner for quality in terms of the clarity of the footprint mark(s) and the quantity of visible morphological features and/or number of footprints available. Through this assessment, the expert would determine whether the case should be accepted and at the same time would also filter out details of the crime provided unwittingly by a liaising law enforcement officer, for example, the suspect's previous convictions or the suspect's relationship to the victim. This type of information is superfluous to the footprint examination and may contextually bias the principal footprint examiner. If the evidence is deemed acceptable, the preliminary examiner would then have two primary tasks. Firstly, they would need to consider whether the footprint or footprints in question are static or dynamic. Indications that a footprint has been created dynamically would include whether the print was placed within a linear sequence of alternating left and right prints, and the observation of a feature described as "ghosting" within the print (Figure 1). Ghosting is the presence of a double image at the rear of the heel and at the apices of the toes of the print where the inner image is darker and the outer image is lighter.[81,82] Ghosting at the heel is believed to relate to a splaying backwards of the plantar fat pad of the heel during the stance phase of walking while at the toes to the lifting of the toes at the start of the swing phase of gait.[81,83] Determining whether a print is static or dynamic is necessary for the later comparison and evaluation phases of the work as like-with-like comparisons should ideally be undertaken in order to account for as many external variable factors as possible.[84]

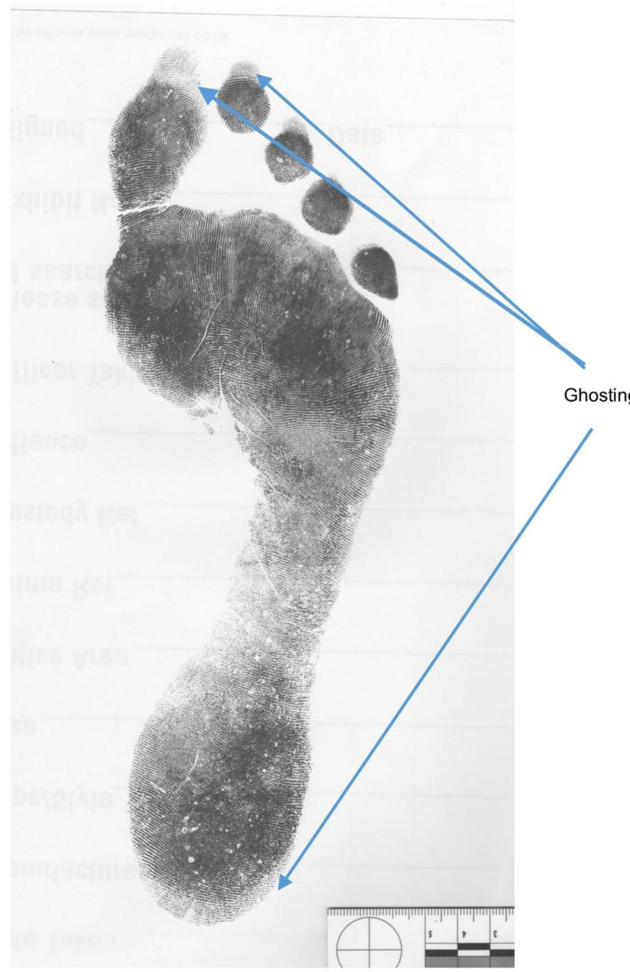

Figure 1 Example of ghosting at apices of toes and rear of the heel seen in dynamic footprints.

Secondly, the preliminary footprint examiner would ensure "reference" or exemplar footprints, are taken from a suspect or a group of suspects, or any person required to be ruled out of the investigation. Reference footprints are usually collected in the form of inked footprints, considered as baseline prints due to the quality afforded by inked marks, the standardisation of the collection method and also the quantity of footprint research involving the analysis of inked footprints.[5,85] Although some research studies have used cyclostyling/fingerprint ink for the collection of footprints,[22,31,66,71] other mediums such as inkless print kits are popular.[14,18,59,83] For the collection of reference footprints for use in the comparison stage, an inkless print kit is most commonly used adhering to standard footprint collection protocols as recommended by DiMaggio and Vernon.[5] Should the questioned footprints indicate that they were formed at the crime scene whilst the owner was moving (e.g. through ghosting), the reference footprints should also be captured in a dynamic state, using dynamic footprint capture protocols.[5,59,70,86,87] The preliminary examiner would then forward the reference and questioned footprints to the principal examiner, ensuring chain of custody protocols are strictly adhered to.[53] Once the footprints have been received, the principal examiner, shielded from contextual bias as far as possible, would then proceed to carry out a forensic examination according to the ACE-V process beginning with an analysis of the reference footprint.

Analysis

Although several methods are available for the description and analysis of footprints the approaches can be classed in two groups; those using linear or metric measurements to connect the periphery of anatomical features of the footprint and those using a non-metric subjective assessment of the outline morphology of the print. Nirenberg[88] recommends a minimum of two different approaches should be used in forensic investigation to gain an aggregate opinion of the dimensional and morphological characteristics of footprint evidence.

The linear measurement approaches for forensic footprint examination include the Gunn method, Optical Centre method, Robbins method, Rossi's Podometric System and more recently the Reel method. Robbins' methods can however be discounted as they are no longer used due to the ignominy which now surrounds Robbins entire work in this field.

Gunn[37] devised an approach in which lines are drawn from the rearmost aspect of the footprint's heel to the foremost aspects of each of the five toes usually present on a print. Similarly, a line would also be drawn across the most medial and lateral aspects of the ball of the footprint (Figure 2). If required, additional lines could be added interconnecting these points, for example, from the medial aspect of the ball of the footprint to peripheral aspects of each of the toes, but in practice, this is rarely undertaken and only if a partial print of the toes and ball of foot is recovered from a crime scene. Although the Gunn method is widely used by practitioners, the original research reporting the use of the method was purely anecdotal and descriptive.

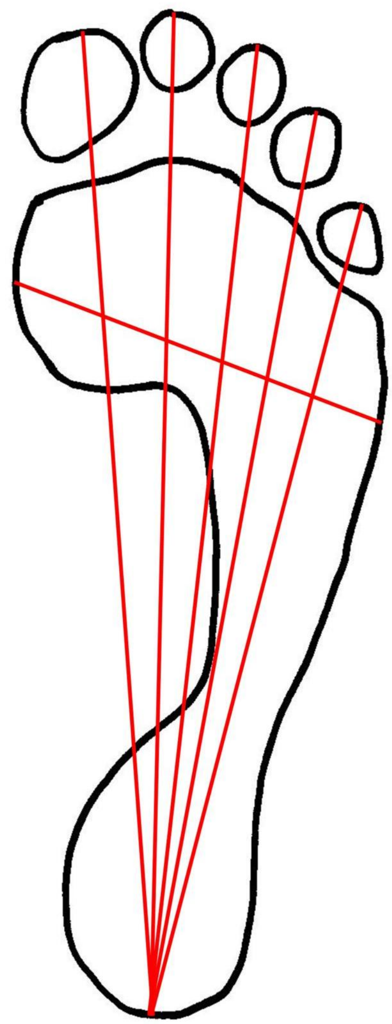

Figure 2 The Gunn method.

The Optical Centre method was described by Bodziak[8] and Kennedy[13] and represents a variation on the connection and measurement of lines drawn between peripheral landmarks of the footprint. Lines are instead drawn to connect what Kennedy described as "the optical centre of the heel to the optical centre of each toe" (p84). An optical centre is located by taking the central point from the best fit of a circle placed in the position of best fit within a feature of the bare footprint (typically a toe) and drawing the line to be measured from that central point (Figure 3). This measurement was described as one of 38 measurements utilised by Kennedy[13] for the measurement of 2000 participants' inked footprints in the first of a series of articles examining the uniqueness of the human footprint. All 38 measurements from each participant were compared with the remaining sample to determine exact matches using a "computer program" (p.84). No other participants shared the same footprint measurements. As the footprints had been collected under the same conditions, the match test was challenged with the inclusion of an arbitrary 5 mm error margin for each measurement. For this amount of variance, the input of 12–15 measurements proved sufficient to exclude all other footprints from the sample. This study does not offer inferential statistical results, and the effect of dependency of measurements and of individual measurements is not reported. The final study by Kennedy et al[14] investigating the uniqueness of the human footprint does not differentiate measurements and it is therefore unclear of the validity and reliability of the Optical Centre method alone.

Rossi described a method which he called his Podometric System that could be used by clinicians, rather than forensic practitioners, to describe foot types through categorising key landmarks of the foot and their relationship to each other.[9] Rossi's system was based on the placement of five longitudinal lines and five lateral lines through prescribed positions relative to the plantar surface of the foot with each set of lines converging at a central

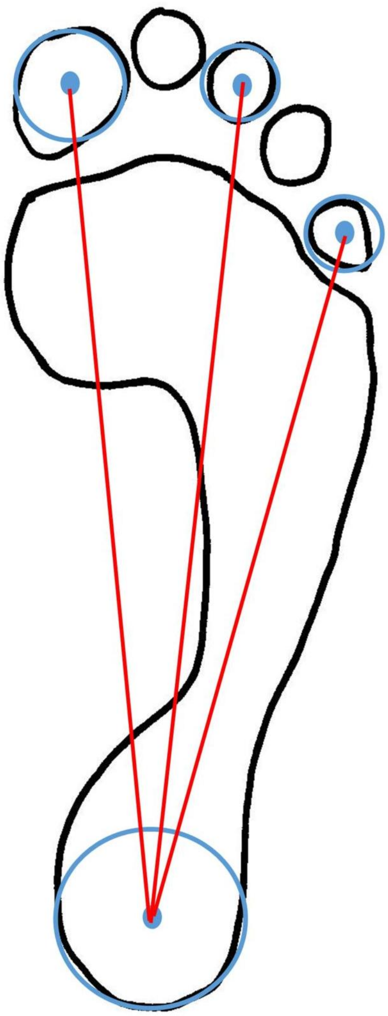

Figure 3 The Optical Centre method.

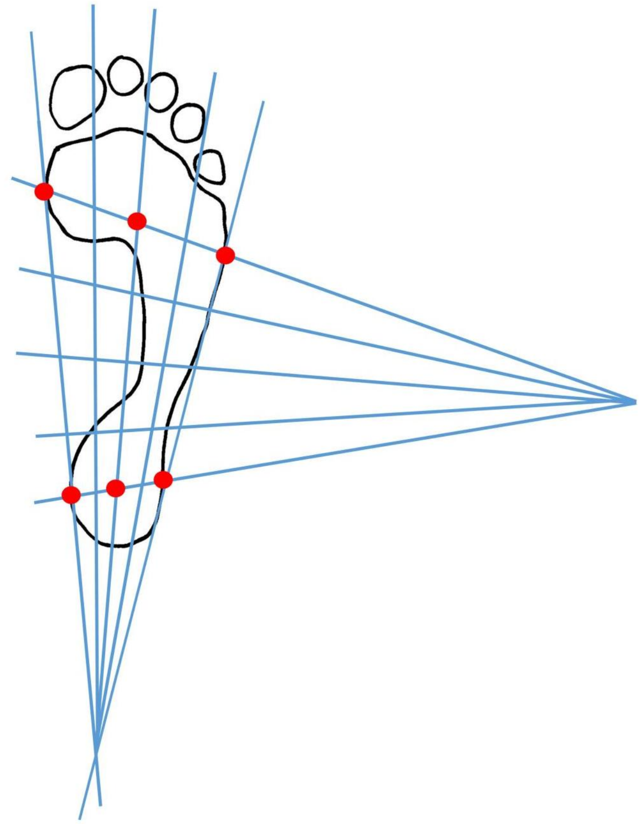

Figure 4 Rossi's Podometric System.

point (Figure 4). Although Rossi did not envisage his methods to be used in the forensic evaluation of footprints, those working in the field of footprints saw this approach as having the potential to be utilised,[89] although to date his methods do not appear to have been tested and used in practice. Again, this measurement method is descriptive only and its validity as a singular measurement method for use in footprint examination is questionable.

For their previously described large-scale study investigating the uniqueness of the human footprint, Kennedy et al later devised a measurement approach which included a central axis to align each footprint vertically for analysis.[14,15] Reel et al[18] adopted this central axis approach by utilizing the inner and outer tangent lines of the footprint[9] with incorporation of Gunn lines (Figure 5). Rather than drawing and recording measurements manually, Reel et al demonstrated high reliability using automated GNU Image Manipulation Program software.[18] For example, the authors used three different statistical tests by way of triangulation to determine intra-rater and inter-rater reliability and suggested inter-rater (three operators) intraclass correlation coefficients (ICC) of 0.99, a standard error of measurement (SEM) ranging between 0.05 and 0.07 mm and Bland–Altman 95% Limits of Agreement (LOA) ranging between −0.83 and 0.4 across all three participants who measured 30 footprints.

The Overlay method[1–3,5,10,16,31,89–91] is an entirely different approach for analysing footprints. Instead of drawing lines between defined landmarks of the footprint to measure specific quantitative dimensions, the method instead relies on the tracing of the outline of footprints along with any features in the bare footprint such as crease marks, scars or fine outline detail (Figure 6).

To facilitate analysis, scale evidence quality photographs are first generated as life size two-dimensional images of both the questioned footprint and the reference print from a known and suspected person.[5] Using a clear transparent acetate sheet and the image of the reference print the morphological outline of the footprint is hand-traced.[5,17,88,91] The reference footprint is usually of higher quality and sharper definition than the questioned print

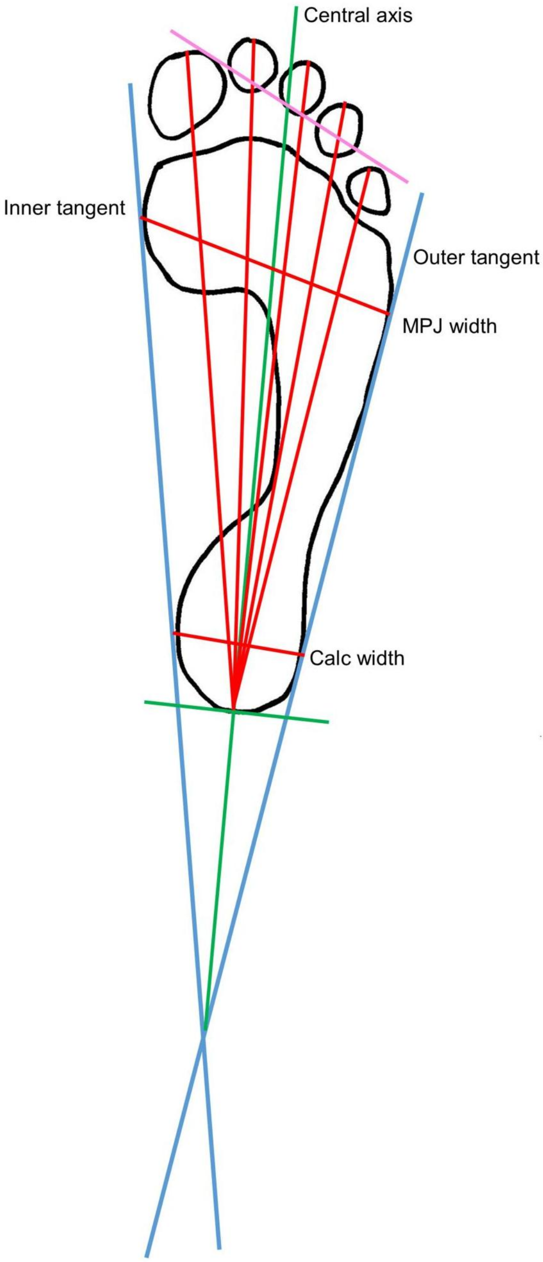

Figure 5 The Reel method.

Figure 6 The Overlay method.

because it has been collected under controlled conditions using an inkless print kit.[5,85] The tracing is produced for later comparison with the image of the questioned footprint, where it is laid over this image to enable the examiner to make visual and subjective comparisons of how well features correspond or differ.[16] When an analysis of the morphology of the footprint is performed, all visible features are traced. DiMaggio and Vernon[5] describe these features as the outline detail in all toe prints, the anterior ball of the footprint, medial arch area and lateral and heel contours (Figure 7). Development of this technique was afforded by DiMaggio[89] who introduced terminology to define certain features even further including the web ridge line (anterior ball of footprint), the web space outline, and lateral, arch and heel lines. Footprint zones were also proposed to permit proportional assessments, such as in cases where partial footprints may be evident.

In response to review recommendations both in the US and in the UK, there is a demand for forensic methods to be validated. With publication of the National Research Council's National Academy of Sciences (NAS) report in 2009, strong recommendations were made for greater scientific rigor to prove the validity of methods of analysis.[50] This was further supported by the President's Council of Advisors on Science and Technology (PCAST) report in 2016, which stressed a priority to evaluate and clarify scientific standards for the validity and reliability of feature comparison

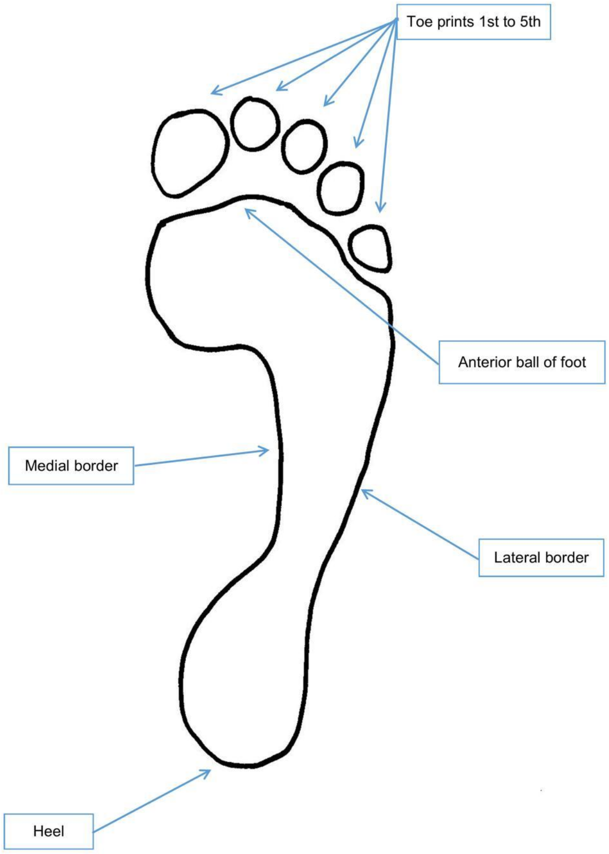

Figure 7 Morphological features of the footprint.

methods.[92] In the UK, the Forensic Science Regulator working under the auspices of the Government's Home Office has outlined requirements for method validation set out in their Codes of Practice and Conduct for Forensic Science Providers document.[53] In this regard, research has been undertaken to ascertain method validity of the linear measurement methods used in footprint examination, which has been systematically reviewed.[2,93]

Reel's work on considering the validity and reliability of the other linear measurement methods demonstrated that the Optical Centre method has lower levels of reliability.[55] This was identified when the method was subjected to repeat measurement testing and compared with other approaches, particularly using more rigorous statistical methods such as 95% LOA and 95% SEM which measure absolute reliability as opposed to, for example, the ICC which measure relative reliability.[55] Reliability of measurements using the Optical Centre method for a sample of 31 male and 30 female adult footprints in static and dynamic states suggested 95% LOA of −4.76 to 3.48 and 95% SEM of 5.31 mm. Of the two remaining methods, Gunn's method proved to have good reliability (95% LOA −1.40 to 1.79; 95% SEM 1.13 mm), while the Reel method demonstrated excellent reliability (95% LOA −0.41 to 0.61; 95% SEM 0.10 mm) (Table 1).

Further to the latter being the current method of choice for forensic footprint analysis, Nirenberg et al demonstrated there were no significant differences between measurements using the Reel method for i) a manual technique with a ruler, ii) GNU Image Manipulation Program and iii) Adobe Photoshop©, in a pilot intra-rater study involving 100 bare footprints.[86]

Research is also being undertaken to assess the validity of the more subjective Overlay method used to compare the similarities and dissimilarities in footprint morphology and is currently being subjected to peer review testing.[94] As this method captures outline features of individuality it would nevertheless still be used routinely in casework in addition to either the Gunn or Reel methods given that it will clearly demonstrate the form, size and placement of large and small features of the footprint for later comparisons.[5]

The questioned footprint recovered from the crime scene is then analyzed using the same methods employed in the analysis of the reference footprint. The analyses of reference and then questioned footprints are completed on separate occasions in order to help guard against the potential for confirmation bias which would affect the forensic comparison processes in general.[95]

Comparison

The comparison of questioned and reference footprints would commence with the Overlay method. As previously described at the analysis stage, the tracing from the reference footprint is overlaid onto the image of the questioned

Table 1 Summary of Analysis of Reliability for the Optical Centre Method (OCM), Gunn and Reel Methods

Method	ICC (95% CI)	95% LOA (Upper Lower)	SEM (mm)	95% SEM (mm)
OCM	0.96 (0.92–0.98)	8.68 −4.76	2.71	5.31
Gunn	0.99 (0.99–0.98)	1.79 −1.40	0.57	1.13
Reel	1.00 (1.00–1.00)	0.61 −0.41	0.05	0.10

Notes: Data from Reel.[55]

print to enable comparisons of the shape, position and overall fit of features.[16] The examiner would look initially to determine whether the overall dimensions of the compared prints are the same, similar, dissimilar or overtly different. The comparisons would take place in the following order: 1) the overall dimensions and morphology of each feature (Figure 7), for example, the size and shape of individual toe prints, 2) the placement of features, for example the toe position in the prints and 3) the finer features captured by the overlay, such as crease marks or scars, in the case of bare footprint examination.

There are a number of approaches to facilitate the examiner's need to record their comparative findings in terms of how compatible or incompatible observed features are. Some use a positive and negative scale to judge the degree of feature compatibility or incompatibility. For example, if the second toe prints were judged to have some compatibility in relation to their shape then a single positive symbol would be recorded. Equally, if comparison showed a higher degree of compatibility then a double positive symbol would be documented. Conversely, the examiner will indicate degrees of incompatibility by using single negative and double negative notations. Another approach is described by DiMaggio[89] who uses a level of certainty framework to indicate degrees of agreement between comparisons of footprint size, shape, position of digits, footprint zones and identification lines. Whichever approach is used, the examiner must use logical expert reasoning to generate subjective judgements of how features compare. Once completed, the overlay comparison could positively rule out the possibility that both prints have been created by the same person due to the presence of major inexplicable differences. If this is not the case, then the comparison would continue by using an objective linear measurement method. In comparing the length of lines of questioned and reference prints the examiner is looking for compared lines that fall within 5 mm of each other, indicating that the prints may have come from the same person. This value was first suggested by William Bodziak in his discussion of the bare footprint database work undertaken by the FBI.[8] Through their database-testing, the research team found that 5 mm was an appropriate margin of error when comparing prints from the same person to "account for any variations in the impression process" (p388).

At this stage, the examiner may also consider the presence of any recognisable and distinguishable features of the foot such as toe deformities and foot type and determine whether these features are, or are not present in both questioned and reference prints.

Evaluation

Evaluation of all information gathered from the analysis and comparison of both questioned and reference footprints would next take place.

The overlay comparison would be considered first with the examiner commenting on whether any similarities or differences would exclude the possibility of both prints having been formed by the same person, whether there are differences which are not so marked as to preclude this possibility or whether there are no notable differences between the compared overlays. Such differences could include grossly larger or different shaped features being present on one compared print and not the other, for example, the toe or heel impressions. Small differences or similarities may be also significant, for example the presence of minor scarring on one print and not the other, or the presence of a distinctive lesion in the same position on both compared prints.

Next, the number of compared lines falling within 5 mm of each other would guide a conclusion as to whether or not the two prints could have been formed by the same person. It is important to note however that the capture of footprints left at crime scenes can be amended by variables, including but not limited to, slippage at the point the print has been formed, change in function (from walking to running), or a turning action as the person has changed direction. Here, the background expertise and experience of the examiner would enable a determination of whether or not any measured or observed differences can be explained by such variable effects.

Once the evaluation of the comparison has been completed, the examiner would produce a conclusion as to what the results of the comparison mean in terms of the likelihood of both compared prints having been created by the same person. In working through the logic underpinning a conclusion, the examiner would consider the level of individuality expressed by a footprint of that size, the form and combination of features demonstrated by the overlay and any foot conditions or features apparent on the print. Here, the examiner would rely on published research, surveys, audit and possibly personal experience to determine the individuality represented by each examined print and through this the strength of conclusion that both compared prints could or could not have been formed by the same person.

At the evaluation stage, it is important to appreciate that the footprint examiner will usually be considering class-level characteristics alone and not identifying, individual or unique-level characteristics. These two different classes of feature have been described by various authors in the context of their own forensic disciplines, including publications relating to footwear,[96] documents,[97] and forensic podiatry.[5] Although class-level and individual-level characteristics have been defined by various authors, there is common agreement that class-level characteristics are those which are incontrovertibly compatible, but not unique, while individual-level characteristics are those considered to be unique.[5] As such, when dealing with an open population it is highly unlikely that a positive identification can be made through the comparison of two footprints unless unique and individualising features are apparent within the compared footprints, for example, ridge detail or scarring. It can, however, be possible to identify the owner of a footprint from a limited range of possibilities where a closed population is under consideration, for example, in a situation where the question is: Which one of these six persons was responsible for leaving footprint A? At the end of an evaluation, the examiner produces an opinion statement as to the level of support the results of the comparison have shown to suggest the likelihood that the compared footprints (questioned and reference prints) could both have been created by the same person.[5] It is however possible to positively exclude someone as being the owner of a questioned print, typically on the basis of significant size and morphological differences. Various frameworks may be used to indicate levels of support in reporting testimonies to the courts. The verbal expressions ranking is one such system used in the UK.[98] Based on the work of Cook et al[99] and Evett at al[100,101] this structure provides the examiner with a hierarchy of expressions to indicate an overall strength of evidential opinion. Ultimately, to reach an opinion, the examiner will consider all combinations of factors including the commonality of features compared between questioned and reference prints whilst acknowledging and factoring in any identified limitations. The latter may relate to the quality of footprints collected or to aspects of the analytical and comparative process. Other systems include DiMaggio's levels of certainty hierarchy,[89] which as previously highlighted for making feature comparisons, can be used to determine opinion by indicating strengths of certainty based on five levels.

Finally, in line with standard forensic practice, the report would be verified by another footprint examiner prior to completion and submission.[102]

Critique of Underpinning/ Supporting Research

The approach to the use of footprints in forensic human identification has been described above, but what is the evidence base which underpins and supports this work? This falls into two main categories; research which has considered the individuality of the footprint and therefore its potential in forensic human identification, and research which tests the ability of examiners and the methods employed to use footprints in identification.

Whilst the question of uniqueness of the morphology of the human footprint as proposed by Kennedy et al[14] has been briefly critiqued in this article, other studies described here are limited in their sample size and/or specific populations. It is essential that more discriminatory studies with larger homogeneous samples are undertaken in order to further understand the subject of the uniqueness of the morphology of a person's footprint. This is particularly relevant for research investigating the intra- and inter-variation of a footprint in terms of states of locomotion (static versus dynamic, and different dynamic situations such as running or walking at multiple speeds), substrates on/in which the footprint has been formed (two-dimensional versus three-dimensional states) and substances in which the footprint has been formed (blood, dust, or ink, etc.), where studies are non-existent or limited. Where studies of this nature do exist, triangulation through repeated studies in different contexts is required. Additionally, whilst various footprint databases are known of anecdotally, these are not widely published and often held on an individual basis with no public access. It is therefore often difficult in casework evaluations to rely on large database information to estimate the probability of footprints belonging to the same person.

Apart from Reel et al[18,55] who tested the inter-rater reliability between novices and an expert for a footprint measurement approach, little research has been carried out to investigate the outcomes of experienced versus non-experienced footprint examiners, to further validate the research evidence-base in this area and to establish standards in practice. Furthermore, to the authors' knowledge, there has been no research carried out regarding the effects of cognitive bias and the forensic footprint examiner. Clearly, further research is needed to understand how the existing research supports footprint examiners in real-world practice and how their expertise and experience in this area compares and contrasts with the research knowledge-base. Attempts have been made to standardise footprint examiner training[103–105] and the advent of the Chartered Society of Forensic Sciences' Certificate of Professional Competence in footprint examinations in the UK allows practitioners to demonstrate their commitment to continuing professional development and competency as a practitioner in this field.[106] This competency test involves a series of multiple-choice questions followed by a three-hour practical examination with opportunity for renewal occurring every three years.[106]

Discussion has been omitted in this review regarding three-dimensional footprints created in soft substrates such as sand or mud. This is due to a paucity of available research pertaining to footprints of this nature, possibly due to the amount of dependent and independent variables necessary for inclusion in these types of studies, and again this area requires further investigation. Also omitted from this review is the more complex area of footprint sequencing. This examines footprint parameters identified from a series of a person's footprints to form measurement understanding for forensic investigation pertaining to foot step and stride length, and to base and angle of gait.[5,107,108] This area of footprint measurement is relevant to forensic gait analysis and does not necessarily focus on footprint morphology, hence its omission.

Summary

This review has included the protocols developed for footprint examination and has identified the underpinning research validating these methods. Although footprint examiners are able to provide valuable assistance to crime scene investigations, they would approach each case with caution. The interpretation of footprint examination comparisons is in need of further empirical inquiry and due to limited databases, conclusions relating to the weight of evidence provided by a footprint examiner for the criminal justice system can only be opinion-based and not fact-based. Forensic footprint examiners can undergo professional competency testing; however, this is not currently mandatory. Priorities for further research include the development of footprint databases for exploring individuality, an understanding of footprint intra-variation and three-dimensional footprint morphology. Finally, in order to fulfil the requirements of the UK Forensic Science Regulator,[53] there is now a necessity for the development of a code of practice for footprint examiners. This need is paramount and its relevance is far reaching to organisations in the United States such as the International Association for Identification (IAI), the American Academy of Forensic Sciences (AAFS), the Forensic Science Standards Board of the National Institute of Standards and Technology (NIST) and the Organization of Scientific Area Committees (OSAC).

Disclosure

The authors report no conflicts of interest in this work.

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