

Forensic Measurement Comparison of Foot Insole Impressions

Abstract:

In forensic podiatry, footprints have been shown to provide a valuable source of discriminatory information. Footprints may be found in various forms, such as bare footprints, sock-clad footprints, or as impressions on insoles within footwear. This study utilized quantitative measures of foot impressions on pairs of insoles from shoes worn by the same person from a population of 31 adults. The measurements were determined by using the Reel method and comprised measurements from the heel to the tips of the toes and width of the ball. The purpose of the study was to assess the margin of error for these measurements to determine whether they were sufficiently accurate for forensic use.

A secondary purpose of this study was to determine whether the analyst's experience or lack thereof in forensic podiatry had an impact on the precision of measurement data. The insole foot impressions were assessed by two podiatrists with forensic podiatry experience in footprint analysis, footprint research, and in using the Reel method of footprint measurement, as well as by three students of podiatric medicine without any such experience. A statistical analysis of the data from the study was performed using SPSS v28 (IBM SPSS Statistics for Windows, Version 28.0. Armonk, NY: IBM Corp). The most reliable measurements were of forefoot width, heel to first toe, heel to second toe, and heel to fourth toe. The greatest variation occurred in the measurements of the heel to the third and fifth toes. The measurements of the forensic podiatrist analysts showed less variability than those of the podiatry students, suggesting that measurement precision is related to the experience of the analyst.

Keywords: Footprint, Insole, Forensic, Podiatry, Footwear

1. Introduction:

Footprints may occur in various forms in criminal investigations. This includes bare, sock-clad, or those found on the insoles[1] of footwear found at crime scenes [1-10]. Footwear may be discovered at crime scenes for a number of reasons, such as intentional removal so as not to leave a shoeprint, or if the footwear falls off during a physical altercation [1, 4]. In these instances, the insole foot impression[2] may provide valuable evidence in determining whether to include or exclude a specific individual as the wearer of the footwear [1, 2, 4, 11-15]. Footwear may also be helpful in identifying post-mortem remains by showing an association of the decedent's foot to a known item of footwear [16].

The examination of insole impressions in forensic assessment of footwear remains relevant despite advances in DNA analysis, as footwear often is found to have mixed DNA and barefoot morphology has been advocated as corroborating evidence [17].

The science that underpins the discriminatory value of an insole foot impression is derived from the human foot's distinctiveness, which has been extensively studied [18-27]. One of the most comprehensive studies was by Jurca et al. [18] which analyzed 1.2 million 3D foot scans and found statistically significant differences in measurements of all foot dimensions considered. This large variation, influenced by the biomechanical effects of the entire human body, results in footprints that are highly individual and personalized [7, 28-33]. While research has found varying levels of footprint individuality, a multi-year investigation by researchers associated with the Royal Canadian Mounted Police found the odds of chance match of a barefoot impression in a general population to be one in 1.27 billion [34]. While variability would

[1] Insoles are also referred to as "footbeds" or "sockliners."
[2] Other terms used for insole foot impressions include "marks" or "prints."

be expected in insole foot impressions, given their lack of detail when compared to a bare footprint, their individuality would be expected to be less than that of a bare footprint [1].

Insole foot impression evaluation is grounded in established principles of forensic physical comparison [1, 35, 36]. These methods are best employed through a "like-with-like" comparison, which compares an insole foot impression of a known individual to that of an unknown insole foot impression (associated with the crime scene). Ideally, both insoles are a similar style. Specifically to insole foot impression analysis, this methodology has been supported by literature and research [1, 15, 36-38]. This “like-with-like” approach is particularly important in insole foot impression examination because the effects of footwear, such as constricting or allowing motion of the foot, influence the impression’s morphology [1, 14, 39].

Foot insole impression analysis has been undertaken with linear measurements, an overlay approach, and/or visual comparison [1, 5, 36-38]. Various linear methods have been demonstrated to be acceptable, including the Gunn Method, the Optical Center Method, and the Reel method. The Reel method has been shown to have high inter- and intra-rater reliability [40] and has been validated on both bare and sock-clad footprints. Moreover, this method has been employed in forensic and non-forensic scientific research [8, 41-45] and accepted in courts in the United States and the United Kingdom [46, 47]. An error margin of ±5 mm has been used in bare footprint research [7, 48], and it is considered an acceptable differential [1, 15].

This study investigates linear measures of foot insole impressions of shoes worn by adults. A secondary purpose of this study was to compare if the analyst’s forensic podiatry experience impacts the precision of measurement data.

2. Materials and methods

2.1. Design

The present study is a two-dimensional quantitative, linear measurement comparison of footprint insole impressions. Informed consent was obtained and the study was conducted in accordance with the ethical standards described in the 1964 Helsinki Declaration and its later amendments.

2.2. Sample

Subjects: Insole donor subjects were volunteers from a podiatric medical school in Philadelphia, Pennsylvania, USA. While 31 pairs of insoles were considered initially, 10 pairs of insoles were excluded from the final analysis. Insoles were removed from the sample pool for several reasons: Subjects 4 and 5 were eliminated because their insoles were from different shoe styles, and the insoles themselves differed in style and construction; Subjects 9, 11, 21, 24, and 26 were excluded due to a lack of a visible foot impression on one or both insoles, preventing identification of the landmarks required to use the Reel method; and Subjects 10, 17, and 31 were excluded due to damage to one of the pair of insoles, which made the landmarks necessary for the Reel method difficult to visualize. Of the remaining subjects, there were a total of 10 males and 10 females, providing a total of 40 insoles. The mean age of the subjects was 27.8 years, and the ages ranged from 23 to 56. Subjects who had an obvious limb or foot abnormality, deformity, or pathology were excluded from the study.

Raters: Two forensic podiatrists with experience in analyzing footprints, performing research on footprints and in using the Reel Method (one with approximately 8 years of experience, identified as P2, and one with four years of experience, identified as P1), and three students of podiatry (identified as S1, S2, and S3).

2.3 Methods

The subject's insoles were removed from their shoes and examined for signs of foot insole impressions. Two insoles from different pairs of shoes from each subject, either both right or both left, as determined by the insole pair with the most visible impressions, were obtained. A ruler was placed beside each insole against a white background, and the insole was photographed with standard forensic photography techniques. This procedure was repeated with each insole to photograph all 31 paired (i.e., two right or two left) insoles.

2.4. Analysis of the footprints and insoles

The GIMP (GNU Image Manipulation Program) was used to measure the distances between anatomical landmarks of each insole foot impression. While the use of other software or manual measurement is acceptable for footprint measurement [45], GIMP was chosen by the authors because it was used by Reel in the original evaluation of the Reel method [40]. Upon using the Reel approach, five lengths and one width measurement were ascertained by recognizing anatomical landmarks on each insole foot impression.

The Reel method involves a measure from the rearmost aspect of the footprint's heel to the foremost aspects of each of the toes, with an additional measurement across the most medial and lateral aspects of the ball of the footprint [40] (Fig. 1). To consistently locate the rearmost aspect of the heel for the toe-length measures, a tangent alongside the inner and outer edge of the footprint is used with the identification of a point of intersection which is bisected. The bisection is traced to the most rearmost aspect of the heel and is referred to as the central axis. The forefoot width (or ball width) measurement transverses the footprint's inner and outer widest points. Measurements were recorded in millimeters. This protocol was used on the insole foot impressions (Fig. 2) by all five analysts.

2.5. Statistical analyses

Descriptive statistics were used to summarize the measurements on insole foot impressions. Independent sample t-tests were performed to ascertain the differences in the measurements on the paired insole foot impressions.

3. Result

Supplementary Tables 1, 2, 3, and 4, along with Figure 3 illustrate the difference in measurement for each analyst for the insole foot impression in the 20 paired (i.e., two right or two left) insoles. The results demonstrated that variation is greater among student analysts. Among the two forensic podiatrists, P2 had the least variation overall. Least difference occurred for both the students and podiatrists, when compared separately and together, in the measurements of the forefoot width, heel to toe 1 and toe 2. The most variation was found in the measurement of the heel to the 3rd and 5th toes, which exceeded the ±5 mm error margin used in bare footprint analysis.

4. Discussion

The process of including or excluding an individual as the possible wearer of worn footwear generally involves examination of the entire footwear item, including consideration of the footwear's insole's foot impression. Essentially, the foot insole impression is the result, in part, of the foot's relationship with the particular item of footwear; unlike a footprint, which typically appears immediately, the insole impression develops over time as the footwear is worn. This insole impression is created from the foot's pressure, moisture and heat. It is also influenced by the footwear style, construction, and fit, which may constrict the foot and/or toes and affects the foot's function and motion. Other possible factors, such as the wearer's activities, his or her occupation, the environment, or particular medical or gait-related issues of the wearer can further influence the insole impression. To this end, a paired comparison of a questioned insole foot impression to a known insole foot impression can assist in accounting for the potential effect of footwear on the foot insole impression and is considered a more robust comparison than with a bare footprint [1, 2, 37, 38].

For both the students and podiatrists, the insole foot impression's measurements of forefoot width, heel to the first toe, second toe and fourth toe had the least amount of variability. These measurements were within a 5 mm difference for all analysts. Given that an insole foot impression generally involves motion of the foot overtime—as opposed to a footprint that forms immediately—the findings of this study suggest that the effect of footwear on an individual's foot in regard to width and the first, second and fourth toes is remarkably similar.

The variation was greatest in measurements from the heel to the third and fifth toes. It is well-established that the fifth toe does not always make contact with the ground [40, 49-51]. Hughes et al. [51] found that roughly a third of their 160 subjects did not use their fifth toe when standing. And during walking, the median contact time with the ground was least for the fifth toe. This lack of contact with the ground may contribute to the variability of the fifth toe's insole impression. The significant difference between a subject's insole foot impressions for their third toe is unclear, though it may involve a similar mechanism as the fifth toe—it does not contact the insole with enough pressure to leave a defined impression. Alternatively, Crowther et al. [39] suggested that the toes within a shoe may be pushed toward the midline of the shoe, rather than free to spread out as when barefoot. Such constriction may act on the third toe to force it slightly upward, lessening its ability to fully contact the insole. Regardless, given the researchers' results, a 5 mm parameter for the third and fifth digit would not be applicable to insole foot impressions. Further, the utility of considering linear measurements from the heel to the third and fifth toes may provide less evidentiary value than the other four measurements.

General variation with all measurements may be due to variation of the motion of the foot in the different footwear. Hammer et al. [37] determined that insole foot impressions are typically larger than bare footprints and suggested that could be due to movement within the shoe. In this respect, Nirenberg et al. [4] found differences between bare footprints and foot insole impressions, and Nirenberg et al. [43] has suggested the occurrence of in-shoe movement has an effect on the formation of insole foot impressions. Even though the footwear styles of the subjects that were used in the final analysis of this study were similar, differences in their construction—such as the pliability of materials encasing the foot—may have allowed for different amounts of movement, accounting for the variation in the foot impressions. Importantly, the findings show similar linear measurements to recognized landmarks, which suggests foot insole impressions can be assistive in including or excluding a person as the wearer of a shoe.

When considering the podiatrist analysts only, the measurement of forefoot width, heel to the first toe, second toe and fourth toe were all within a 5 mm difference. Overall, the podiatrists' measurements showed less variation than those of the students. These results demonstrate that experience with forensic podiatry improves precision in linear measurement comparison of foot insole impressions. Notably, the podiatrist with more experience had less variable measurements than the lesser experienced podiatrist. These findings suggest the importance of training, education, and practice in understanding the human foot and forensic podiatry when undertaking foot insole impression assessment. The results show that the trier of fact in criminal proceedings should consider the analyst's experience in forensic podiatry when weighing the evidentiary value of the findings presented in regard to insole foot impression measurement. This could be of particular importance when the trier of fact is faced with disparate measurements from different analysts. Recognizing the value of experience is not new; Lucock noted this point in 1979, stating in part, "[a] knowledge of normal and abnormal foot function and foot deformities and their effect on footwear is required…" [52]

The previously noted elimination of some of the insoles from the final analysis due to issues with the quality of the foot impression or in cases where subjects wore different style shoes highlights the importance of comparing insole foot impressions from similar footwear.

In actual criminal matters, even if the style of footwear differs, a comparison will still be made. In this scenario, the evidentiary value of the comparison would likely be less than if the footwear style were the same. The more similar the footwear, in theory, the more accurate the comparison, assuming all other factors are equal. Although when approaching a criminal matter, the circumstances of the case will impact the comparison process. The authors recommend, when possible, that analysts avoid reliance on only using a linear measurement approach when evaluating insole foot impressions. They suggest combining measurements with a visual assessment methodology. Such advice has also been given by others [1, 5].

With respect to the quality of the insole foot impression, two categories are considered: the quality of the insole itself and the quality of the insole foot impression. In considering the insole itself, if it was damaged (e.g. torn) or worn to the point of fragmenting or disintegrating such that the foot impression was altered, the insole was removed from further evaluation in the study. For the insole foot impression, if the landmarks to utilize the Reel method were not visible, it was eliminated. In criminal casework, these factors would not necessarily eliminate an insole from assessment, though if assessed, any quality issues should be considered in the analyst’s conclusions.

Further investigations into comparison of insole foot impressions utilizing linear measurements should be explored using more diverse subject populations and a greater number of insole pairs and more analysts, as these issues were limitations of this study. Other footwear styles should also be examined as well as other measurement approaches, including giving consideration to the effects of subject’s weight and the biomechanics of the subjects’ foot.

Future research may also include exploring new technologies to image insole foot impressions and the motion of the toes in various styles of footwear with particular focus on furthering the understanding of impressions formed by the third and fifth toe.

5. Conclusion

This study analyzed the comparison of two-dimensional linear measurements of foot insole impressions from different shoes from the same individual using the Reel method. For the measurements of the forefoot width, heel to the first toe, second toe and fourth toe, less than 5 mm difference was found. For the heel to third and fifth toes, a greater variation was observed, which exceeded 5 mm. The study also explored the differences in measurements between podiatrists with forensic podiatry experience and podiatry students who had no forensic experience, finding that forensic podiatry experience improves precision by reducing variability.

The study reinforces the forensic comparison “like-with-like” approach for foot insole impression comparison and the scientific value of using insole foot impressions to include or exclude an individual as the wearer of a worn shoe. The authors hope this research generates further interest in exploring the analysis of insole foot impressions and increases awareness of the potential assistance and limitations in the linear measurement examination of insole foot impressions. The research also demonstrates the value of having such assessments performed by experts who have the requisite knowledge and experience in such matters. This could ultimately provide the criminal justice system with opinions supported by a strong scientific foundation.

6. References

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Figure 1

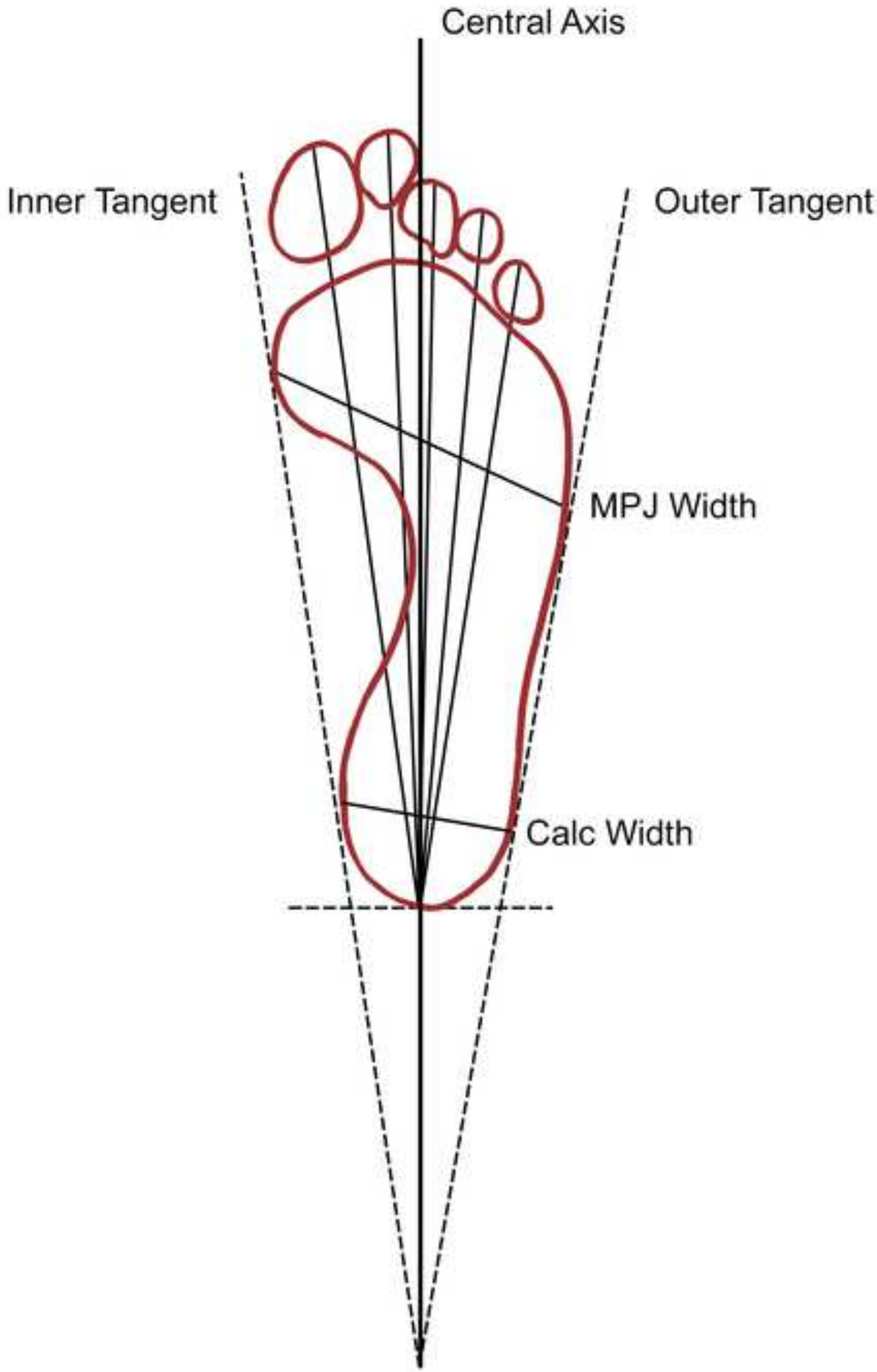

Central Axis
Inner Tangent
Outer Tangent
MPJ Width
Calc Width

Figure 2

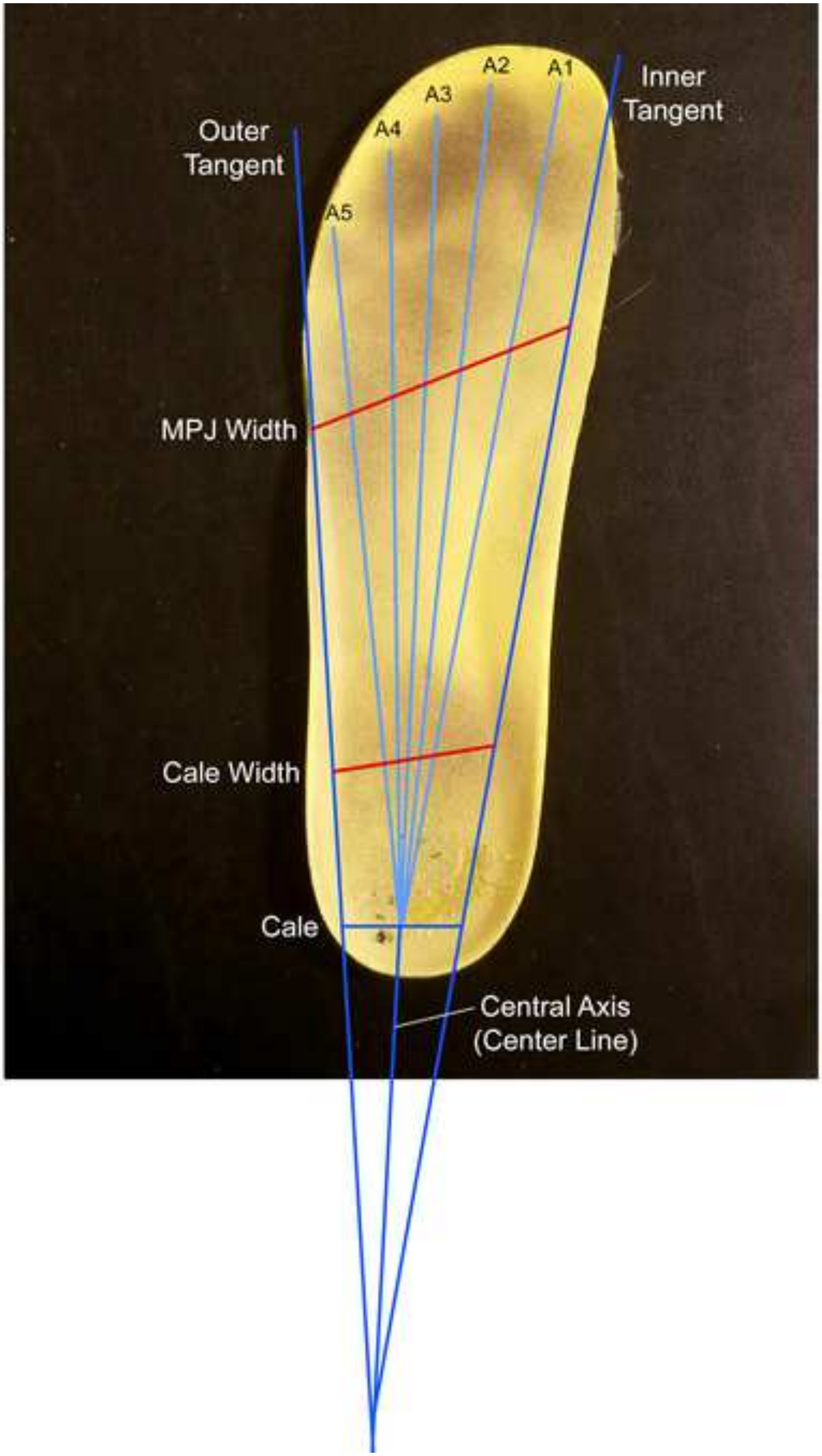
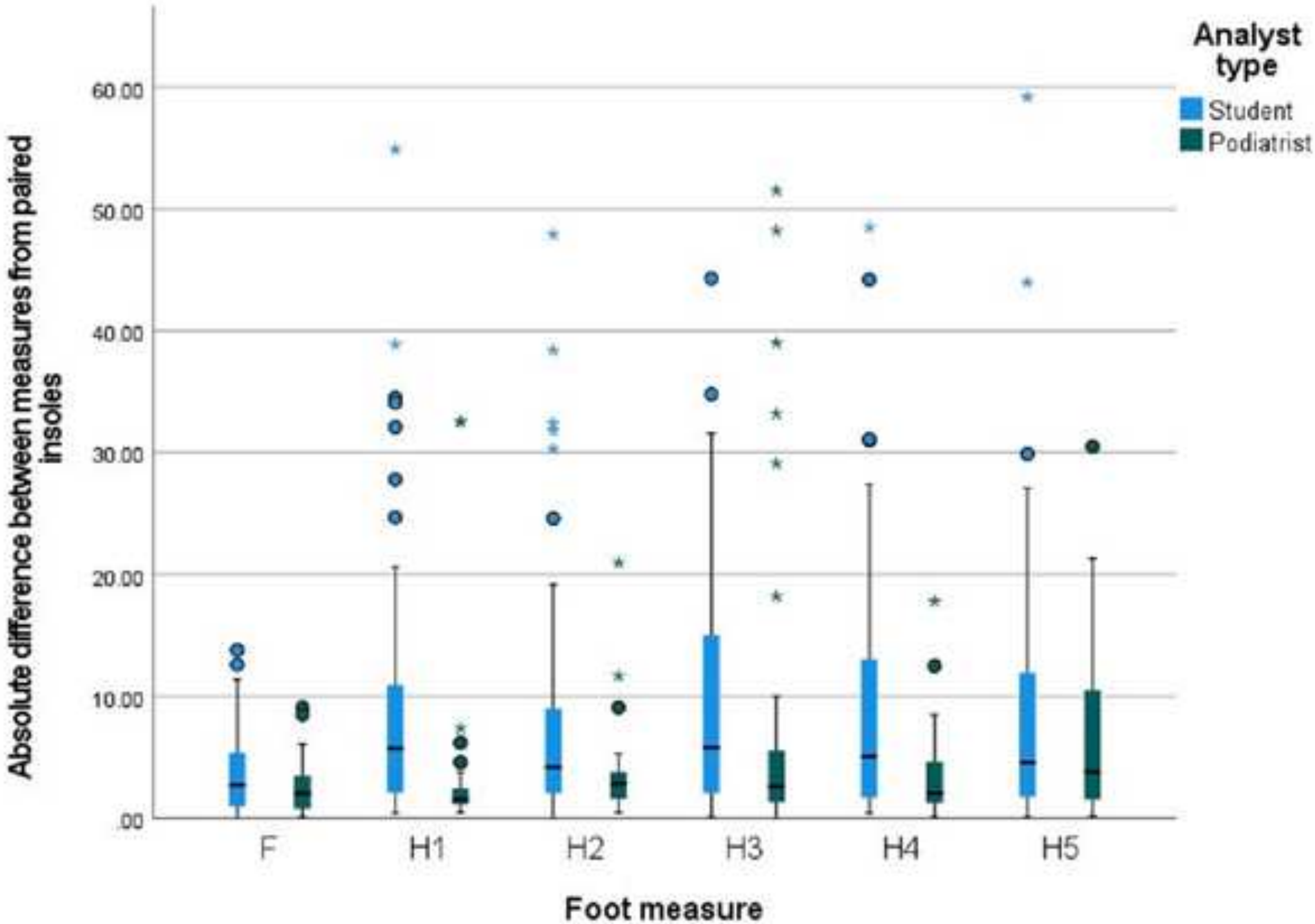

A1
A2
A3
A4
A5
Inner Tangent
Outer Tangent
MPJ Width
Calc Width
Calc
Central Axis (Center Line)

Figure 3


Analyst type
Student
Podiatrist
Absolute difference between measures from paired insoles
60.00
50.00
40.00
30.00
20.00
10.00
.00
F
H1
H2
H3
H4
H5
Foot measure

Captions for Figures

Figure 1. Depiction of the Reel Method of two-dimensional measurement of a bare footprint.

Figure 2. Depiction of the Reel Method of two-dimensional measurement for use on an insole foot impression.

Figure 3. Boxplot showing the difference measures between paired insole foot impressions obtained by students compared to podiatrists. F = forefoot, H1-H5 = heel to toe measures. The filled boxes represent the inter-quartile range (IQR), the horizontal line represents the median value. Mild outliers (more than 1.5 x IQR above first quartile or below second quartile) are represented by circles, extreme outliers (more than 3 x IQR) by stars.

Table 1

Descriptive statistics showing absolute differences in measurements

	N	Mean	Std. Deviation
Abs_diff_F_S1	20	3.36	3.65
Abs_diff_F_S2	20	4.12	3.99
Abs_diff_F_S3	20	3.57	2.64
Abs_diff_F_P1	20	2.70	2.38
Abs_diff_F_P2	20	2.32	1.98
Abs_diff_H1_S1	20	10.38	10.54
Abs_diff_H1_S2	20	13.43	13.49
Abs_diff_H1_S3	20	4.69	7.08
Abs_diff_H1_P1	20	3.60	7.02
Abs_diff_H1_P2	20	3.41	6.96
Abs_diff_H2_S1	20	8.54	10.00
Abs_diff_H2_S2	20	10.98	12.57
Abs_diff_H2_S3	20	5.27	6.78
Abs_diff_H2_P1	20	3.98	4.52
Abs_diff_H2_P2	20	2.97	2.30
Abs_diff_H3_S1	20	9.55	9.52

Abs_diff_H3_S2	20	12.58	11.52
Abs_diff_H3_S3	20	5.39	7.13
Abs_diff_H3_P1	20	13.14	18.31
Abs_diff_H3_P2	20	2.44	1.65
Abs_diff_H4_S1	20	11.20	11.25
Abs_diff_H4_S2	20	12.16	12.10
Abs_diff_H4_S3	20	5.17	7.49
Abs_diff_H4_P1	20	4.10	4.53
Abs_diff_H4_P2	20	2.76	2.01
Abs_diff_H5_S1	20	9.77	10.61
Abs_diff_H5_S2	20	13.27	13.52
Abs_diff_H5_S3	20	4.02	6.48
Abs_diff_H5_P1	20	11.06	7.34
Abs_diff_H5_P2	20	2.92	4.50

S = student, P = forensic podiatrist, F= forefoot, H = heel

Table 3

Group Statistics

	Analyst type	N	Mean	Std. Deviation	Std. Error Mean
Abs_diff_F	Student	60	3.6800	3.43017	.44283
	Podiatrist	40	2.5100	2.16934	.34300
Abs_diff_H1	Student	60	9.4998	11.13013	1.43689
	Podiatrist	40	3.5025	6.90238	1.09136
Abs_diff_H2	Student	60	8.2610	10.17297	1.31333
	Podiatrist	40	3.4750	3.57375	.56506
Abs_diff_H3	Student	60	9.1733	9.85352	1.27208
	Podiatrist	40	7.7900	13.18526	2.08477
Abs_diff_H4	Student	60	9.5050	10.75432	1.38838
	Podiatrist	40	3.4325	3.52750	.55775
Abs_diff_H5	Student	60	9.0183	11.11013	1.43431
	Podiatrist	40	6.9900	7.27401	1.15012

F= forefoot, H = heel