Research paper

Two-dimensional linear analysis of dynamic bare footprints: A comparison of measurement techniques

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ABSTRACT

In forensic intelligence-gathering, footprints have been shown to be valued evidence found at crime scenes. Forensic podiatrists and footprint examiners use a variety of techniques for measuring footprints for comparison of the crime scene evidence with the exemplar footprints. This study examines three different techniques of obtaining two-dimensional linear measurement data of dynamic bare footprints. Dynamic bare footprints were gathered from 50 students from a podiatric medical school using the Identicator® Inkless Shoe Print Model LE 25P system. After obtaining 100 bilateral footprints from the participants, the quantitative measurement data were collected by using three different measurement techniques: (i) a manual technique using a ruler (direct technique); (ii) an Adobe® Photoshop® technique; and (iii) a GIMP (GNU Image Manipulation Program) technique. The seven Reel linear measurement methodology was used for producing measurements using these three techniques.

This study showed that all the mean bare footprint measurements on the right and left feet obtained using the direct technique were larger than those obtained using GIMP and Adobe® Photoshop® images. Differences were also observed in measurements produced using GIMP software and Photoshop images. However, the differences observed in the three techniques used for bare footprint measurements were not found to be statistically significant. The study concludes that there are no significant differences between the three measurement techniques when applied to two-dimensional bare footprints using the Reel method. It further concluded that any of these measurement techniques can be used when employing the Reel methodology for footprint analysis without significant difference.

1. Introduction

The two-dimensional analysis of footprints is significant in forensic science and other specialties, including anthropology, biomechanics, and medicine, in that abundant information can be obtained [1–7]. The first use of footprints in the forensic context is documented in 1862 when bloody footprints at a murder scene were linked to the perpetrator [8]. The modern forensic use of footprints began in the 1970s when podiatrist Norman Gunn began using scientific methods to measure and compare footprints at crime scenes to those of suspects [9–11]. Since then other experts have continued to provide extensive footprint evidence analysis [12–14].

Footprints can be individualizing by examining aspects such as papillary ridges, lengths and widths of a footprint, and other measurements [15–19]. In the absence of papillary ridge evidence, two-dimensional bare footprint measurements can be useful in determining individualization. Bare footprints have been shown to provide information on a suspect's height, body weight, and gender [17,20]. Partial footprints have also proven to provide vital forensic identification information [21].

There have been a number of methodologies of footprint measurement used in the past [11,12]. The Reel methodology of two-dimensional footprint measurement has been shown to have a high intra-rater reliability and intra-class correlations of 0.98 to 0.99 with a 95% standard error measurement in controlled settings [22]. The Reel method of footprint analysis is considered as a baseline measurement system in forensic podiatry research, since it is not affected by the height and body weight of a subject. The original protocol for the Reel methodology utilizes the GNU Image Manipulation Program (GIMP) software to measure and adjust footprints for analysis. Other software

and measurement techniques, such as Adobe® Photoshop®, have been developed and advanced but have not been evaluated as reliable measurement tools for the Reel method.

Research conducted by Reel et al. [22] used the GIMP measurement program based on its cost effectiveness, stability, and ease of measuring and recording of lines and angles. GIMP is an open source program, allowing it to advance and debug more rapidly under peer review. Other measurement programs are considered to be less desirable for a variety of reasons, such as cost and accessibility of the program. Manual or direct measurements were not used in an effort to reduce human, systematic, and random error sources. While Adobe® Photoshop® is considered to be the industry gold standard for processing forensic images [23], this program was not selected because it was difficult to measure linear and angular values. Adobe® Photoshop® is also considered a closed program system—a proprietary or commercial software—which does not offer the same previously stated benefits as open systems. Moreover, Carrier analyzed open and closed computer systems for forensic uses and concluded that open digital measurement programs meet *Daubert* standards for court admissibility [24]. Koch and Schneider concluded the open systems allow for a more generalized use and community acceptance [25]. These two factors may be considered additional benefits of using GIMP over Adobe® Photoshop® in the original Reel two-dimensional linear measurement methodology.

While the GIMP software that was selected for use of the Reel method was based on practical reasons, few studies have addressed differences in quantitative measurements between programs. In botanical sciences, Jorgensen et al. concluded that GIMP and Adobe® Photoshop® measured percentage vegetation cover consistently between the two software programs [26]. Gutierrez-Vilahu et al. demonstrated that Adobe® Photoshop® is a reliable and valid technique to assess and measure footprints in healthy and Down syndrome (trisomy 21) individuals [27,28]. Specifically regarding the Reel method, Burrows examined the use of Adobe® Photoshop® and the Reel method [29]. Burrows stated that Adobe® Photoshop® "offers a reasonable easy method for measurements" [29]. Burrows' study compared various Reel measurements of footprints obtained from dissimilar collection devices; however, the comparison of digital measurement systems was not the focus of the study. The current pilot study compares three different quantifying measurement modalities using the Reel method: Direct technique with a standard ruler, GIMP software, and Adobe® Photoshop® software.

2. Materials and methods

2.1. Design

This pilot study is a quantitative test comparison. Linear measurements were taken from dynamic bare footprints at various landmarks using three different quantitative measurement modalities. Each participant was informed of the intentions of the study and signed an informed consent prior to participation. The study was conducted in accordance with the ethical standards described in the 1964 Helsinki Declaration and its later amendments.

2.2. Sample

Fifty students and staff from Barry University School of Podiatric Medicine, Miami, FL, USA, were recruited as participants for the study. There were 30 males and 20 females who participated in the study, providing a total of 100 dynamic footprints. Healthy participants without any apparent/obvious limb/ft abnormality or deformity were included in the study. This sample was previously analyzed for other bare footprint research with different, unrelated objectives [30].

No calculations for sample size were performed because no prior study has been done on this issue in forensic podiatry. The aim of this study was to determine if the Reel method's linear measurements were

Fig. 1. Identicator® Inkless Shoe Print Model LE 25P System being used to collect footprints from a subject.

significantly different based on the measurement technique used, specifically, ruler measurements, Adobe® Photoshop® software, and GIMP software.

2.3. Materials

The Identicator® Inkless Shoe Print Model LE 25P system (Fig. 1) was used to collect footprints. The coater measures 8 × 15 in., and the inkless impression sheet measures 7 × 14 in. The inkless system—the area on which the participants walked during data collection—and participants' feet were cleaned before and after each subject's data was collected. The inkless system and participants' feet were cleaned with antibacterial wipes. The area of collection was swept and cleaned with antibacterial wipes or a Swiffer® Wet Jet™.

2.4. Methods

A mid-gait protocol was employed to mimic an individual's natural walking style [31,32]. Participants began from a defined point, designated with a piece of tape. Footprints were collected on a hard, flat surface to avoid any three-dimensional irregularities [22]. Participants took 10 steps, beginning with the right foot. They then turned and took 10 steps back to the original starting point. Seven meters of walking space was allotted to participants to take full and natural strides. The procedure was repeated three times without footprint collection. Researchers marked the placement of the third and fifth step in the walking cycle for the right foot.

On the fourth trial, the inkless coater was placed at the third and fifth step of the participant's walking cycle. Impression sheets were secured at the corners with tape. The trial was repeated until an acceptable footprint was collected that included the entire footprint. The trials were repeated for the left foot using the fourth and sixth steps in the gait cycle.

2.5. Analysis of footprints

Once 100 footprints were obtained from the 50 participants, the prints were scanned into PDF format using an office series multi-function printer/scanner. Previous literature noted asymmetry between the left and right foot, allowing for both feet from each participant to be included in the analysis [33–35].

Data collected included seven (7) length and width measurements taken from each footprint (Fig. 2) according to the protocol developed by Reel et al. [22,36]. A central axis, heel (Calcaneus; CALC) width of
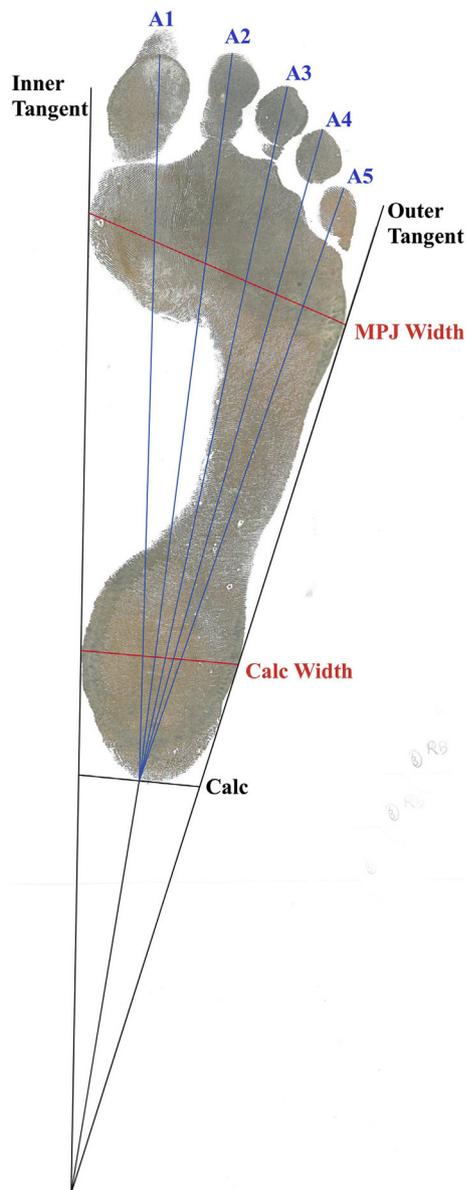
Fig. 2. Length and width measurements as defined by the Reel method (Adapted from Nirenberg et al. [30]).

Fig. 3. Length and width measurements illustrated on a bare footprint being measured by hand using a standard measurement ruler (A manual technique or a direct technique of measurement).

footprint.

The Photoshop (Fig. 4) and GIMP (Fig. 5) trials used the PDF scans of each footprint. Adobe® Photoshop® CC 2018 Version 19.1.4 and GIMP version 2.18.14 software were used. The footprint data files were opened using the respective software. Inner and outer tangents and their bisection were performed first. A line parallel to the most posterior aspect of the heel was then drawn. The distal-most aspect of each digit was measured, followed by the widths of the ball of the foot and heel.

The seven measurements were recorded using a Microsoft® Excel sheet. A separate sheet was created for each measurement technique. Participant information was also entered into the spreadsheet in a separate file. All seven Reel linear measurements were completed by one researcher. Once each of the three measurement techniques was completed on all 100 footprints, the data were statistically analyzed.

2.6. Statistical analysis

The data obtained were analyzed using IBM SPSS® version 16.0 software. Descriptive statistics were performed for comparisons of the barefoot measurements on the right and left feet based on direct measurements, GIMP, and Adobe® Photoshop® images. One-way ANOVA analysis was applied to determine if statistically significant differences existed between the seven bare footprint measurements using the three techniques. Statistical significance was set at $p < 0.05$.

3. Results

A summary of participant characteristics is summarized in Table 1. The seven bare footprint measurements using the Reel methodology were conducted using three different techniques: measurements conducted directly by ruler, using GIMP software, and using Adobe® Photoshop®. Mean values for the different bare footprint measurements are

the foot, ball of the foot width (metatarsophalangeal joint; MPJ) width, and a measurement for each toe (A1 to A5) were obtained based on the Reel linear measurements. The CALC width and MPJ width of the foot were measured from the most lateral to most medial aspects of the footprint. Then, the central axis was formed by bisecting the inner and outermost tangents. A horizontal line from the most posterior aspect of the calcaneus was drawn perpendicular to the central axis. From this intersection, the most distal aspect of the 1st through 5th digits were measured, giving measurements A1–A5. All the measurements were taken in centimeters.

In the direct measurement trials (a manual measuring technique using a ruler), the original prints were placed on a hard and flat table. A standard U.S. measuring ruler and pencil were used to trace the inner and outer tangents of the footprints. The tangents were then bisected. A line parallel to the most posterior aspect of the heel was then drawn. From the intersection of these lines, each of the most distal aspects of each toe was measured (Fig. 3). If a digit did not leave an impression, it was marked "N/A". The width of the ball of the foot and width of the heel were taken from the most medial to the most lateral aspects of the

Fig. 4. Length and width measurements illustrated on a bare footprint using Adobe® Photoshop® measurement technique.

shown in Table 2. The authors observed that all mean bare footprint measurements on the right and left side using the direct technique (manual technique) were larger than those obtained using GIMP and Adobe® Photoshop® images. Differences were also observed in measurements collected using GIMP software and Adobe® Photoshop® images. The differences observed between the three techniques, however, were not found to be statistically significant for all seven linear measurements of the Reel methodology (Table 3).

4. Discussion

With the advancements in technology, digital measurement programs are being developed and updated quickly and frequently. However, it is rare that digital measurement programs are directly compared. Even more uncommon is the comparison of the digital measurement programs in the forensic context. While Gutiterrez-Vilahu et al. concluded that Adobe® Photoshop® was a reliable and valid technique for assessing footprints in two populations; it did not compare these results to other measurement techniques. The authors found only one study comparing two digital measurement programs using EBSCO and PubMed databases. Burrow compared GIMP and Adobe® Photoshop® and concluded that no differences were found between the measurements in the two programs [28]. However, this was not the main focus of the Burrow's study and a more directed study was warranted to further investigate this hypothesis. The results of this study show that there are no significant differences between the direct measurement technique, the GIMP digital measurement technique, and
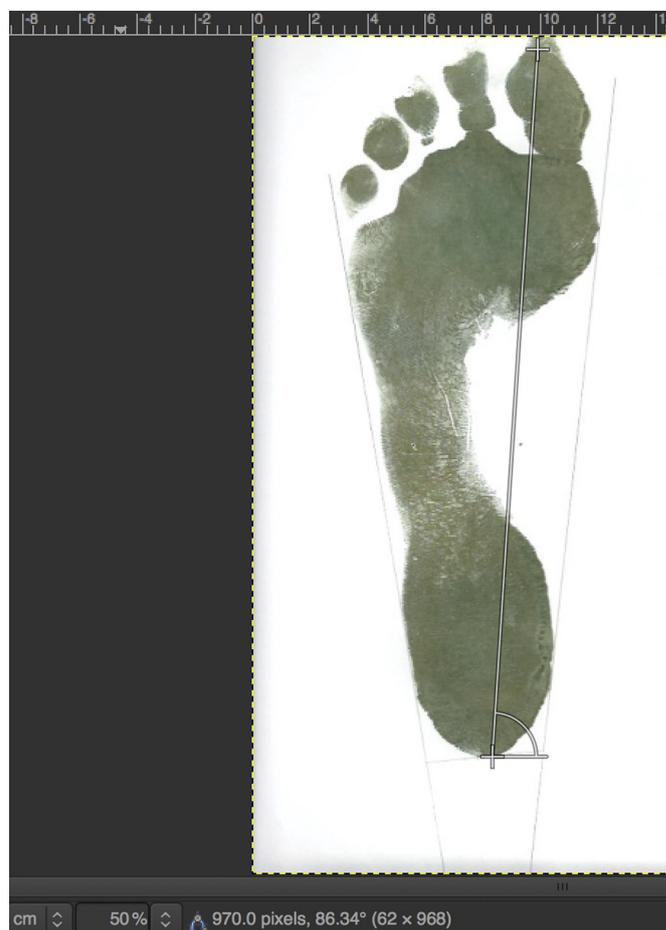

Fig. 5. Length and width measurements illustrated on a bare footprint using GIMP measurement technique.

Table 1
Participants Demographics.

	n	Percent	Mean
Age (years)			28.2
20–29	40	0.8	
30–39	7	0.14	
40–49	0	0	
50–59	2	0.04	
60–69	1	0.02	
Race			
Caucasian	23	0.46	
Asian	13	0.26	
Hispanic	9	0.18	
African-American	5	0.1	
Gender			
Males	30	0.6	
Females	20	0.4	

Adobe® Photoshop® digital measurement technique when using the Reel method to obtain two-dimensional linear measurements of dynamic bare footprints. This is consistent with previous literature of forensic and non-forensic fields [26,28].

In forensic two-dimensional measurement research and application, GIMP software is employed when using the Reel method of footprint analysis because it was originally used during the Reel method's development and testing. Due to the fact that the Reel method has such high intra-rater reliability and intra-class correlations, it is commonly applied in forensic analysis of footprints. The Reel method developer chose the GIMP system because it is an open source program with user-

Table 2
Descriptive statistics for bare foot measurements using the three techniques.

Variable	N	Direct Mean	SD	GIMP Mean	SD	Photoshop Mean	SD
Right MPJ Width	50	09.5640	0.76652	09.5152	0.74548	09.4594	0.76130
Right Calc Width	50	05.1260	0.41530	05.0242	0.47570	04.9662	0.46894
RightA1	50	25.2340	1.70424	25.0256	1.65805	25.1014	1.67900
RightA2	50	25.0930	1.69079	24.9612	1.68399	25.0026	1.68238
RightA3	50	24.1210	1.67506	24.0162	1.68577	24.0288	1.68644
RightA4	50	22.8516	1.58080	22.7306	1.57633	22.7122	1.57898
RightA5	48	21.0669	1.47509	21.0413	1.45403	21.0418	1.46403
Left MPJ Width	50	09.5210	0.75917	09.4844	0.75375	09.5542	0.74815
Left Calc Width	50	05.1190	0.45399	05.0242	0.46031	05.0368	0.47200
LeftA1	50	25.1770	1.77796	24.9722	1.72476	24.9976	1.74168
LeftA2	50	25.1120	1.73748	24.9556	1.71681	24.9942	1.73250
LeftA3	50	24.2380	1.68049	24.0336	1.66033	24.0716	1.68697
LeftA4	50	22.9140	1.64037	22.7664	1.56874	22.7998	1.57691
LeftA5	46	21.2161	1.46482	21.0595	1.42867	21.1140	1.43289

Table 3
Comparison of the three techniques using one-way ANOVA.

Variable	Sum of Squares	df	Mean Square	F-value	*p*-value
Right MPJ Width	0.274	2	0.137	0.239	0.788
Right Calc Width	0.654	2	0.327	1.587	0.208
RightA1	1.113	2	0.556	0.197	0.821
RightA2	0.454	2	0.227	0.080	0.923
RightA3	0.327	2	0.164	0.058	0.944
RightA4	0.569	2	0.285	0.114	0.892
RightA5	0.019	2	0.010	0.005	0.996
Left MPJ Width	0.122	2	0.061	0.107	0.898
Left Calc Width	0.265	2	0.133	0.620	0.539
LeftA1	1.246	2	0.623	0.204	0.816
LeftA2	0.664	2	0.332	0.111	0.895
LeftA3	1.182	2	0.591	0.210	0.811
LeftA4	0.599	2	0.300	0.118	0.889
LeftA5	0.565	2	0.283	0.136	0.873

friendly and stable qualities. However, in recent years Adobe® Photoshop® and other digital measurement programs have also evolved to become more user-friendly, firm and stable. The findings of this study show that Adobe® Photoshop® or direct measurement (ruler) techniques can be substituted for GIMP software when employing the Reel method of footprint analysis. In criminal justice cases, this allows for expert witnesses and prosecutors to examine footprint evidence analyzed with the Reel method using any of the three measurement techniques based on what is deemed most applicable, available, and/or necessary for the particular case at hand.

There is potential for further investigation within the study. One point raised in the original Reel method thesis is the user-friendly aspects of GIMP. This can contribute to reliability of measurements between program users. While only one examiner completed measurements in this study, future studies can test the reliability of measurements using all three measurement techniques to determine if user-friendly qualities of the program are a warranted factor to consider when selecting the program to be used in forensic research or application. Forensic podiatrists and other experts should also consider which programs they are most familiar and comfortable using to ensure that this does not factor into their analyses.

Additionally, the original thesis of the Reel method mentions other digital measurement techniques, such as Adobe® PageMaker® and Autodesk's AutoCAD®r13 software. Adobe® PageMaker®, a discontinued desktop publishing computer program introduced in 1985 by Aldus, was suggested by Natarajan and Cecil as a suitable alternative for measurements [37]. Autodesk's AutoCAD®r13 software program was suggested by Kennedy for construction and linear measurements of footprints [38,39]. Neither of these digital measurement programs was included in this study due to lack of availability. Future research can investigate if either of these digital measurement programs has significant measurement differences from GIMP using the Reel linear measurement method.

Finally, this study was limited in that it was carried out on a small sample of students at a small college in Miami, Florida, USA. This creates the potential for a selection and population bias within the study subjects. Future studies should assess a larger and more diverse population to allow for greater generalization and "real world" application of the conclusion.

5. Conclusion

This pilot study analyzed the differences and/or similarities that may exist between different measurement techniques when applied to the seven linear two-dimensional bare footprints of the Reel method. No significant differences were found between any of the seven measurements taken by direct measurement, using GIMP software or using Adobe® Photoshop®.

This conclusion establishes that any of these measurement techniques can be employed in forensic investigation, criminal justice proceedings, and research when using the Reel linear measurement methodology. As this study only utilized the Reel method, any extrapolation of this study's findings to other methods of footprint forensic analysis should be done with caution.

Conflict of interest statement

The authors declare that there is no conflict of interest regarding this manuscript.

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