# Reliability of a two-dimensional sock-clad footprint linear measurement method


## Abstract

A two-dimensional linear measurement approach for footprints, herein referred to as the “Reel Method,” has been shown to be valid and reliable when used on bare footprints, however, few measurement approaches have been examined on sock-clad footprints. The present investigation examines the validity and reliability of the Reel Method as a two-dimensional linear measurement approach for use on sock-clad footprints.

A walking, mid-gait footprint was collected from 30 volunteer participants using the Identicator Inkless Shoe Print Model LE 25P system. The width of the ball of the foot, calcaneal width, and distance from the most posterior aspect of the heel to the most distal aspect of the first toe were measured and compared between and within three raters. The statistical analysis demonstrated high reliability of the Reel Method among these three raters. The data were found to be normally distributed, and measurements were consistent between and within raters. 95% Intraclass Correlation coefficients, 95% Bland-Altman Limits of Agreement and 95% Standard Error of Measurement determined high statistical agreement between and within raters, demonstrating that the Reel Method is reliable and thus valid for the linear measurement of sock-clad footprints.



**Key Words:** Footprint; Sock-Clad footprint; Measurement; Forensic, Reel Method

## 1. Introduction

The examination of footprints has been used in a wide range of specialties, including podiatric and biomechanical analysis, orthopedics, anthropology, and case analysis for criminal justice purposes [1-7]. In the forensic science context, literature has suggested that footprints are individualistic in nature, and research by Kennedy et al. purports that the odds of a chance match of a footprint is statistically one in 1.27 billion [8-12]. In fact, the analysis of footprints has been used to associate individuals to crime in many countries [8, 9, 13].

Methods of comparing a footprint found at a crime scene to that of a suspect's donated footprint include approaches such as a visual (or overlay) method, focused mainly on morphological characteristics, and two-dimensional measurement approaches [8, 9, 14]. The variety of approaches to footprint measurement suggests the need for an approach with sufficient scientific rigor, which led Reel to lead the development of a two-dimensional linear measurement method (i.e., the Reel Method) [15, 11].

The Reel Method provides a framework to consistently choose reference points that linear and/or angular measurements can be taken from to assess and compare the distinctiveness of known and unknown footprints. This method has also been used to assess and estimate a footprint donor's stature among other uses [16-21]. Moreover, this method has also been applied to insole footprint analysis in the forensic realm and in general scientific research [22-24] and accepted as admissible evidence in legal proceedings in the United States [25] and the United Kingdom[1]. The Reel Method has been shown to have a

[1] R v Kenway 2017, Bradford Crown Court; R v Fletcher 2018, Sheffield Crown Court; R v Morgan 2018, Oxford Crown Court

high reliability with an intraclass correlation coefficient of 0.99 for both intra- and inter-rater conditions [11].

While the Reel Method has been used in numerous applications, including on sock-clad footprints, the validity and reliability of this approach have only been evaluated on bare footprints [26, 11]. This study examined sock-clad footprints. A sock-clad footprint is defined as the impression of the plantar surface of the foot that results when the maker of the footprint is wearing a sock [26]. Nirenberg et al. conducted a comparison of the linear measurements of sock-clad and bare footprints utilising the Reel Method and found no significant differences [26]. Intuitively, the authors assert that the Reel Method should translate as a measurement approach from bare footprints to sock-clad footprints; however, this assumption has not previously been investigated. Sock-clad footprints may vary due to sock thickness, style, and/or stitching, and the potential for shifting and bunching, potentially affecting the Reel Method's validity and reliability.

The present study seeks to determine the validity and reliability of use of the Reel Method as a two-dimensional linear measurement approach to sock-clad footprints.

## 2. Methods

The study was a repeated-measurement design that evaluated the Reel Method of measurement on collected sock-clad footprints. Footprint donor participants were volunteers comprised of 19 males (63.33%) and 11 females (36.67%) with a mean age of 31.2 years. Most participants were Caucasian (46.67%) and right-handed (85.2%). All demographics are summarised in Table 1.

Table 1

Demographic data of participants (N=30). Includes age, sex, handedness, ethnicity, height and weight.

| | Minimum | Maximum | Mean | Std. Deviation | |
|---|---|---|---|---|---|
| Age | 20.00 | 58.00 | 31.20 | 9.17 | |
| Weight_kg | 50.85 | 122.58 | 80.72 | 17.38 | |
| Height_m | 1.57 | 1.83 | 1.73 | 0.07 | |
| BMI | 19.00 | 43.00 | 26.80 | 5.15 | |
| Sex | | Frequency | Percent | | |
| Valid | Male | 19 | 0.63 | | |
| | Female | 11 | 0.37 | | |
| | | | | | |
| Ethnicity | | Frequency | Percent | | |
| Valid | Asian | 5 | 0.17 | | |
| | Hispanic | 7 | 0.23 | | |
| | Caucasian | 14 | 0.47 | | |
| | Black/Caucasian | 1 | 0.03 | | |
| | Filipino | 1 | 0.03 | | |
| | Haitian | 1 | 0.03 | | |
| | Other | 1 | 0.03 | | |
| Handedness | | | | | |
| | | Frequency | Percent | Valid Percent | Cumulative Percent |
| Valid | Right | 23 | 76.7 | 85.2 | 85.2 |
| | Left | 3 | 10 | 11.1 | 96.3 |
| | Both | 1 | 3.3 | 3.7 | 100 |
| | Total | 27 | 90 | 100 | |
| Missing | | 3 | 10 | | |

No participant had any noticeable foot deformities or reported any walking impairment. All participants received verbal and written details of the study prior to participation and were allowed to stop the experiment or ask questions at any time. Due to the benign risks of the footprint collection methodology and the non-identification of the participants' identity, ethical review was not required.

Footprints were collected from each participant using the Identicator Inkless Shoe Print Model LE 25P system, which allows footprints to be collected without leaving visible residue on the participants or their socks. The coater was 8 x 15 inches, and the inkless impression sheets measured 7 x 14 inches. The coater and walking area were cleaned with bleach wipes before and after each participant, and participants used their own socks during the experiment. This method of footprint collection is relatively simple and has been used by researchers in prior studies [11, 22, 26] without any detrimental consequences or infection issues.

A midgait protocol was selected for the study, where the fifth step footprint of the participant was recorded on the impression paper (right foot) [27, 28]. Participants were allowed two or three practice runs without being recorded with at least 10 feet of walking length to ensure a natural stride on a hard, flat surface. Participants started from a marked designated point, and trials were repeated until the participant's entire footprint was captured on the impression paper. This protocol was strictly adhered to by all participants to be certain that all footprints were obtained under standardised conditions.

When 30 right sock-clad footprints were collected, the footprints and demographic data was coded for autonomy. Only the right footprints were collected due to high symmetry between right and left feet [29]. The footprint impression sheets were scanned onto a MacBook computer using an HP Envy 4520 series scanner at 600 DPI.

*2.1 Measurements*

The width of the ball of the foot (MPJ width), calcaneal width (calc width), and distance from the most posterior aspect of the heel to the most distal aspect of each toe were measured (A1-A5) [15] (Fig. 1). To ensure a consistent posterior heel point for toe-length measurement, the inner and outer tangents were followed to a point of intersection and bisected. The bisection was followed to the most posterior aspect of the heel, known as the central axis. From this point, the length to the most distal aspect of each toe was measured. Research has demonstrated that failure to adhere to this protocol results in a higher rate of variability in measurements [7, 30]. The width measurements were taken from the inner and outermost points of the footprints at the widest points. All lengths and widths were measured in millimeters using GNU Image Manipulation Program (GIMP) version 2.10. Although other systems have been studied for electronic and visual footprint measurement, GIMP software was selected for use to reduce any confounding variables in the study and to adhere to the original Reel Method protocol [11, 15]. All data were analysed using IBM SPSS software (Version 26.0 SPSS Inc., Chicago, IL).

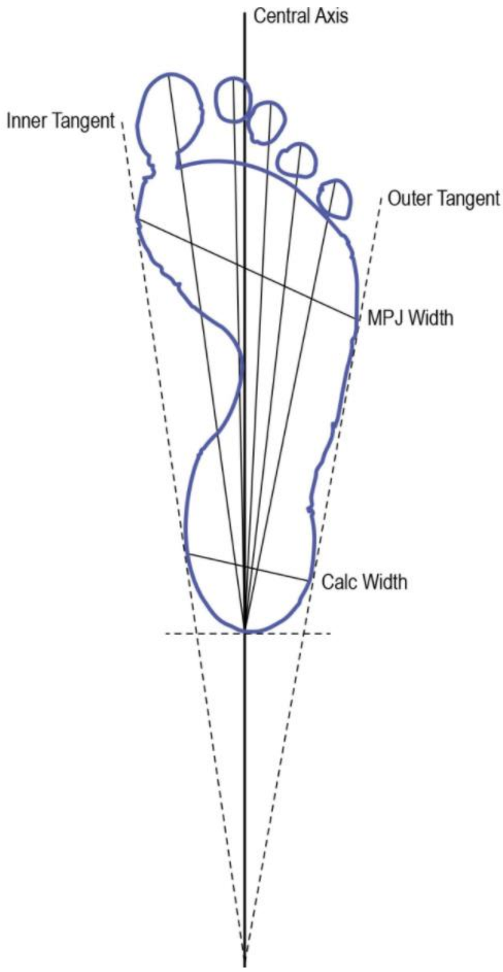


Fig.1. Reel linear measurements to measure the width of the ball of the foot (MPJ width), calcaneal width (Calc width), and distance from the most posterior aspect of the heel to the most distal aspect of each toe print.

*2.2 Statistical Analysis*

A sample size of thirty footprints was selected for the study. According to Cohen [31], given a medium to large effect size, a sample number of thirty will allow for approximately 80% power, the minimum amount of power suggested for a repeated measures study.

Shapiro-Wilks and Kolmogorov-Smirnoff tests for normality showed that all data were suitable for parametric testing. The reliability of the measurements was determined using a one-way random effects model intraclass correlation coefficient (ICC), based on values provided by a prior analysis of variance ($ICC_{3,1}$). The one-way model stipulates that all variance detected by the statistical test is assumed to be measurement error [32, 33].

The Standard Error of Measurement (SEM) was used to determine bias and is a measure of absolute reliability, unlike the less robust Standard Error. For a true value within 95% CI limits, the formula 1.96 x SEM was applied. Bland-Altman plots of 95% limits of agreement (LOA) allowed for a visual representation of the absolute error that exists between the raters' repeated measurements in millimeters [34]. Ninety-five percent confidence intervals for the mean differences of the intra- and inter-rater measurement results were also assessed.

**3. Results**

Shapiro-Wilks & Kolmogorov-Smirnoff tests were statistically insignificant ($p>0.05$); therefore, data were normally distributed. As all length and width measurements have previously demonstrated similarity [11, 15] the Calc-A1 (heel print to 1st toe print) and MPJ width (across the ball of the footprint) were selected for further rigorous reliability analyses. These two measurements were chosen in order to challenge to the reliability analyses. In the relevant forensic podiatry community, the MPJ width is considered to be the most difficult to measure consistently due to the difficulty in locating appropriate anatomical landmarks. Similarly, the Calc-A1 length is thought to be the least stable of the accepted length measurements as it has to contend with the variation of the medial longitudinal arch, which not only 'gives' more than the lateral border during gait due to tendon laxity and a greater number of articulations, its variability is also subject to genetic, ethnic, weight and age factors (Saltzman & Nawoczenski, 1995; Dowling et al., 2001; Thompson & Zipfel, 2005) Rater 3 demonstrated the least agreement among raters (Tables 2 and 3). However, the error bar graphs illustrate the close agreement between the means across the raters' measurements (including Rater 3) and the similar amount of variation exhibiting in all length and width measurements (Figs. 2 and 3).

Table 2

Length measurement averages and standard deviations within Raters 1, 2, and 3.

| Measurement | Mean (mm) | Min (mm) | Max (mm) | SD |
|---|---|---|---|---|
| Rater 1 Calc_A1 Original | 252.71 | 223.90 | 282.70 | 15.62 |
| Rater 1 Calc_A1 Repeat | 252.00 | 224.90 | 279.10 | 15.13 |
| Rater 2 Calc_A1 Original | 251.36 | 228.90 | 251.36 | 12.39 |
| Rater 2 Calc_A1 Repeat | 251.28 | 229.20 | 280.50 | 12.20 |
| Rater 3 Calc_A1 Original | 251.66 | 224.00 | 278.70 | 15.07 |
| Rater 3 Calc_A1 Repeat | 251.46 | 224.10 | 278.70 | 14.89 |

Table 3

Width measurement averages and standard deviations within Raters 1, 2, and 3.

| Measurement | Mean (mm) | Min (mm) | Max (mm) | SD |
|---|---|---|---|---|
| Rater 1 MPJ Width Original | 94.46 | 79.20 | 107.40 | 7.35 |
| Rater 1 MPJ Width Repeat | 94.84 | 80.80 | 108.00 | 7.41 |
| Rater 2 MPJ Width Original | 94.95 | 80.40 | 108.30 | 7.22 |
| Rater 2 MPJ Width Repeat | 95.01 | 80.20 | 109.00 | 7.41 |
| Rater 3 MPJ Width Original | 91.56 | 77.10 | 104.90 | 7.02 |
| Rater 3 MPJ Width Repeat | 90.63 | 75.70 | 105.70 | 7.62 |

Bland-Altman plots of 95% LOA for 3 raters displayed closeness of the upper and lower boundaries (+/- 2 standard deviations around the mean value) for all repeated length and width measurements, suggesting the measurement of sock-clad footprints was consistent both between and within raters (Figs 4-9). Therefore, the method is reliable and valid. However, 95% LOAs for Rater 3 show the widest variation for length and width measurements, as indicated by the error bar graphs (Figs 2 and 3).

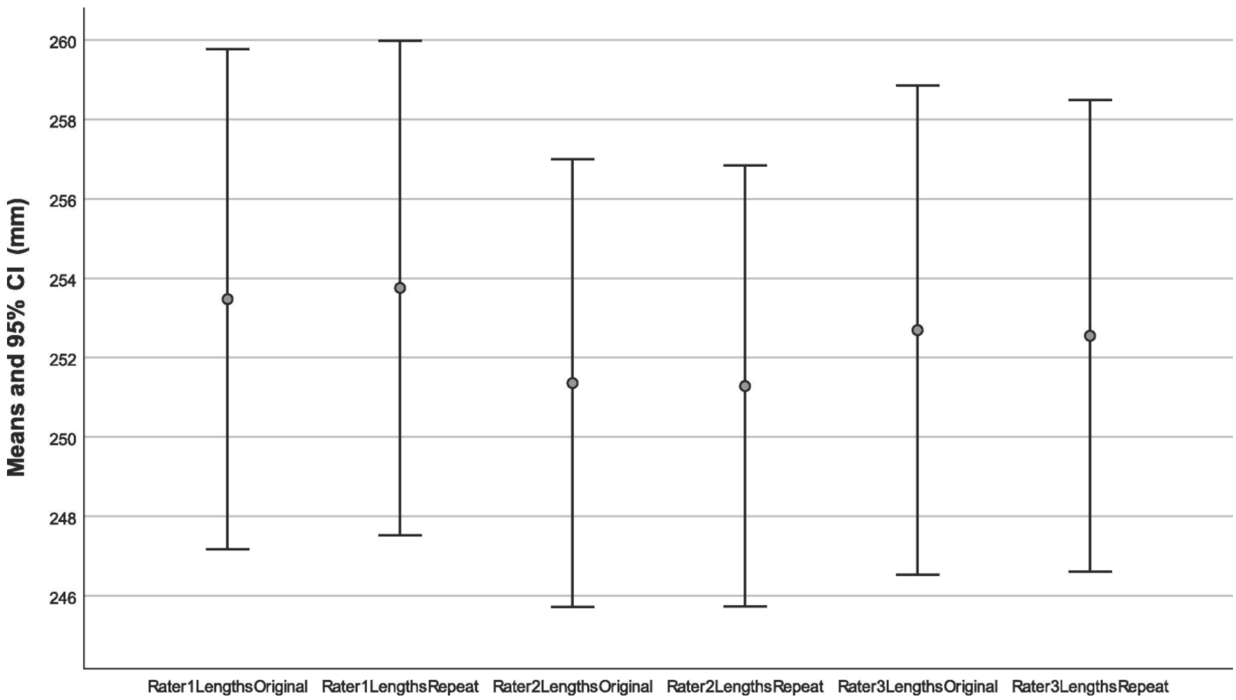


Fig. 2. Graph of error bar illustrating means and 95% CI of repeated measurements of Calc_A1 length between raters.

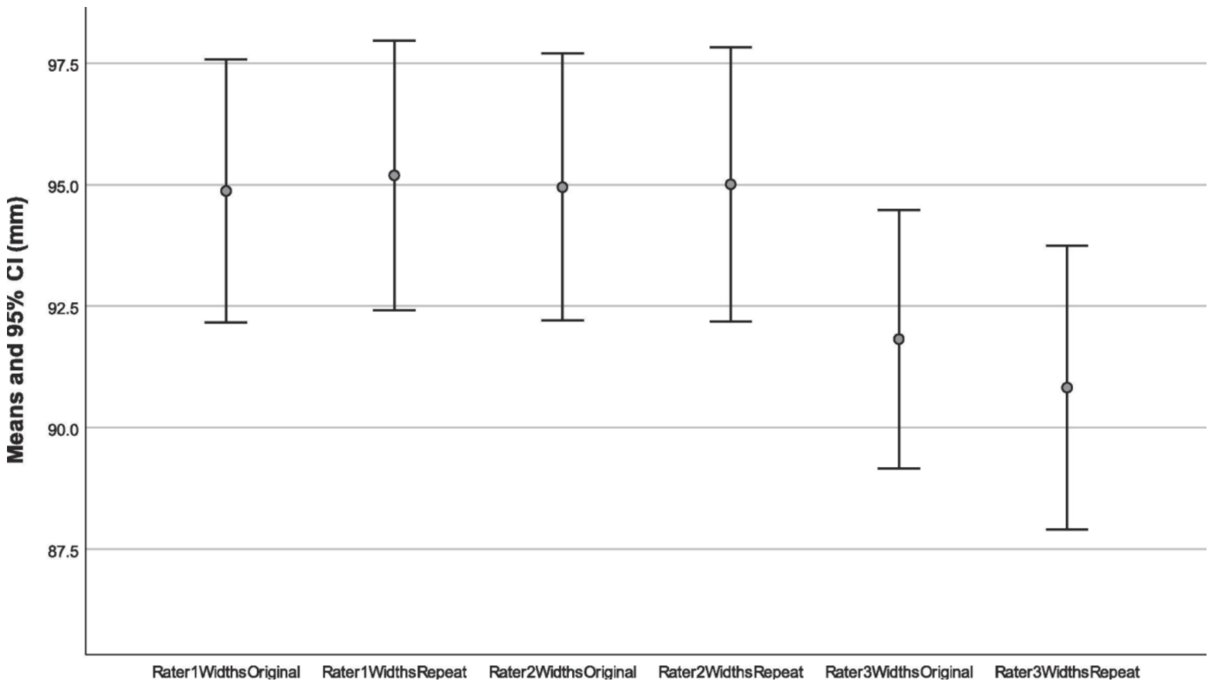


Fig. 3. Graph of error bar illustrating means and 95% CI of repeated measurements of MPJ width between raters.

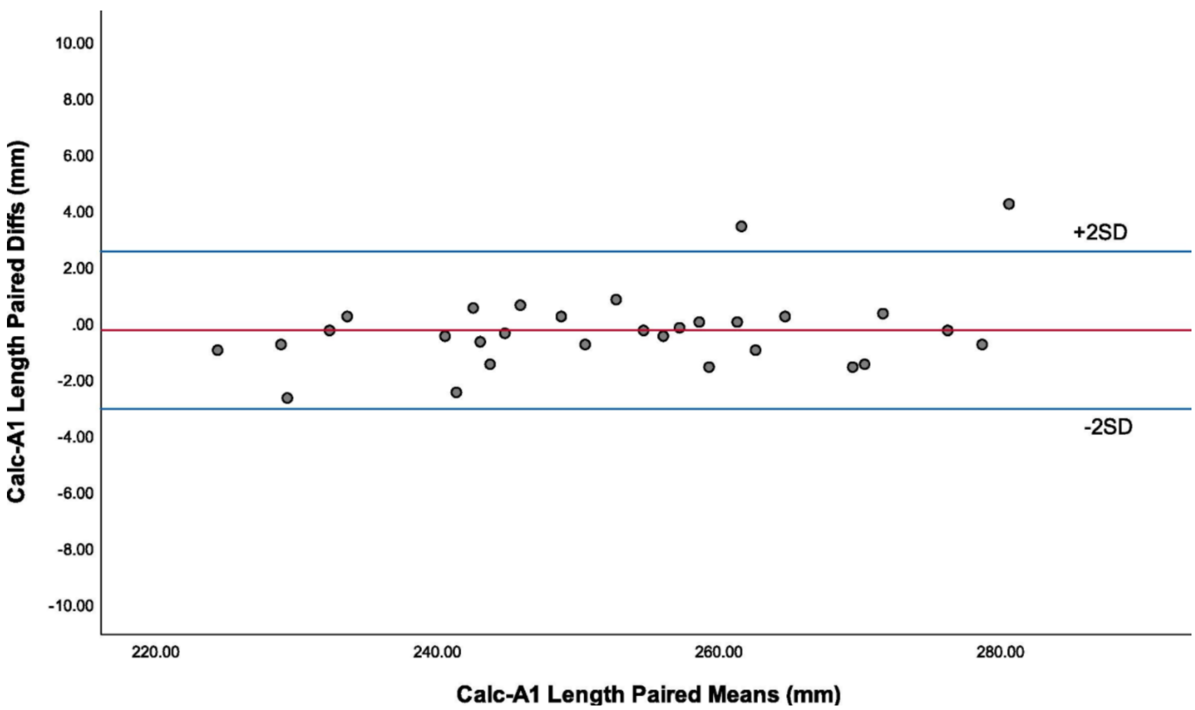


Fig. 4. **95%** LOA graph for Rater 1 for Calc_A1 length repeated measurement (n = 30).

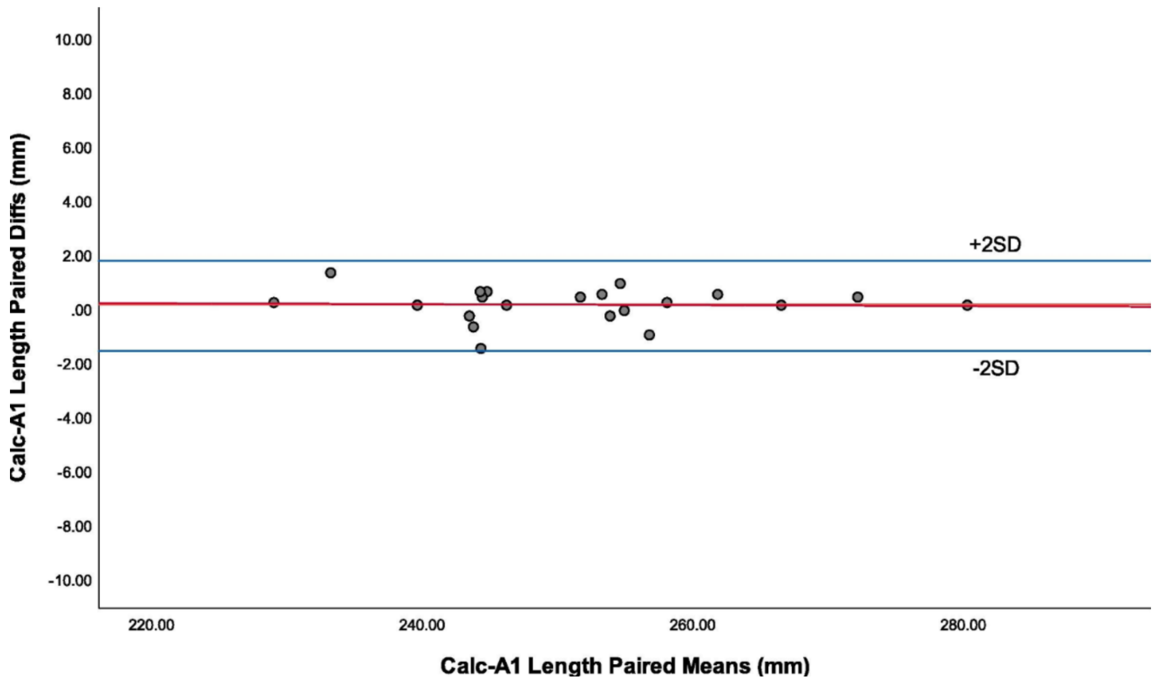


Fig. 5. **95%** LOA graph for Rater 2 for Calc_A1 length repeated measurement (n = 30).

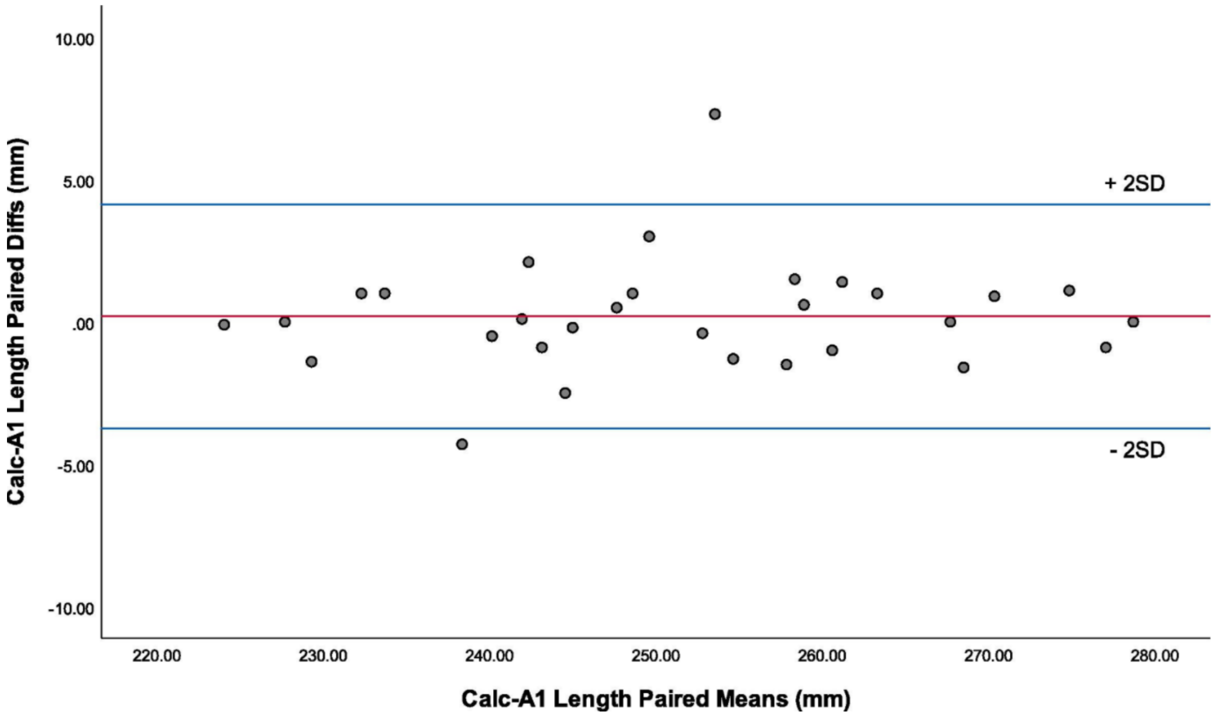


Fig. 6. **95%** LOA graph for Rater 3 for Calc_A1 length repeated measurement (n = 30).

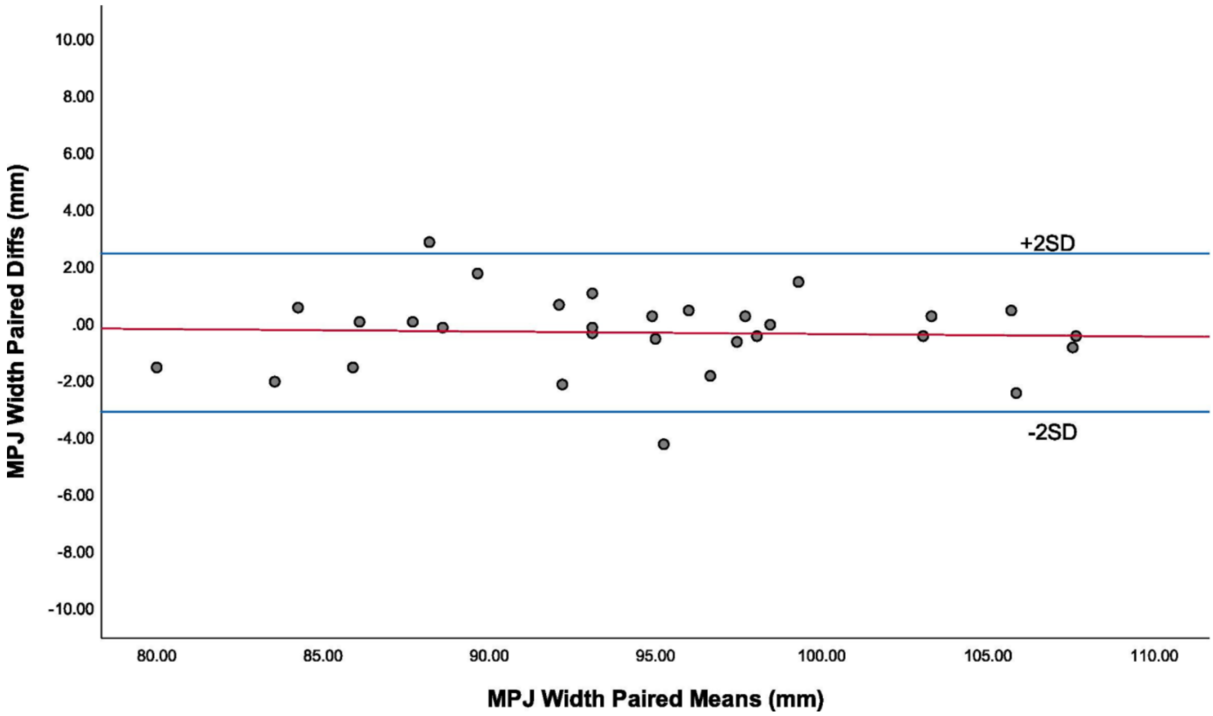


Fig. 7. 95% LOA graph for Rater 1 for MPJ Width repeated measurement (n = 30).

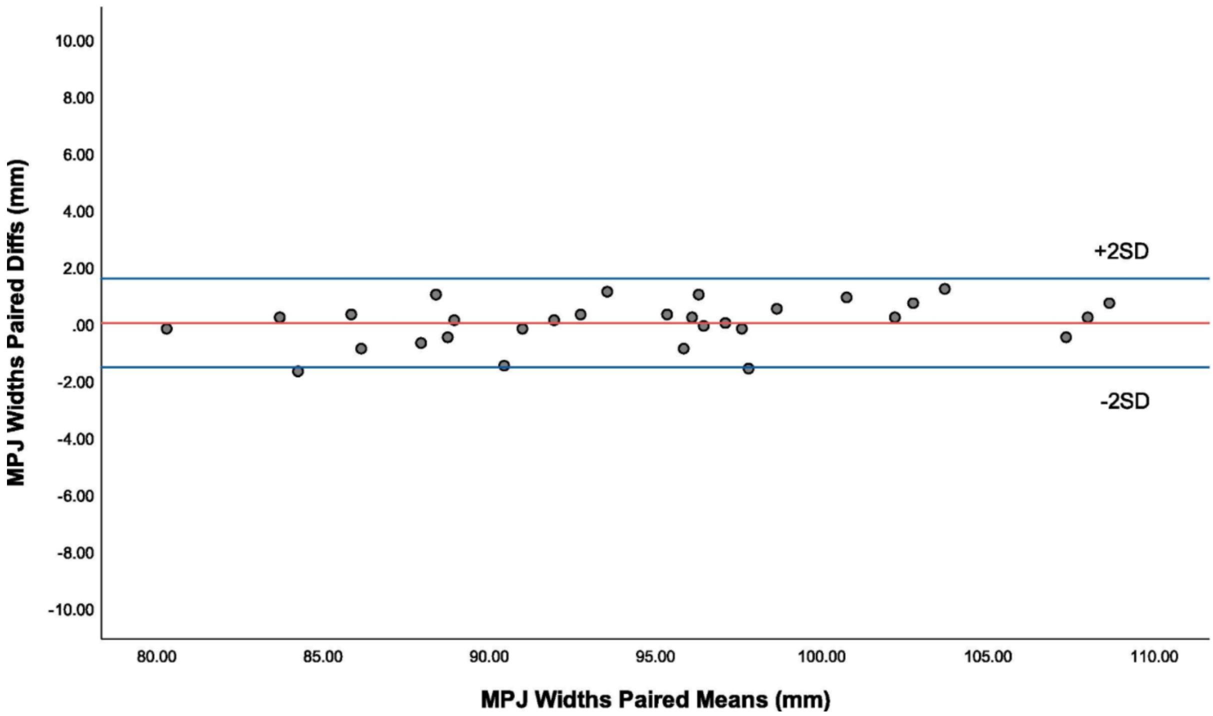


Fig. 8. 95% LOA graph for Rater 2 for MPJ Width repeated measurement (n = 30).

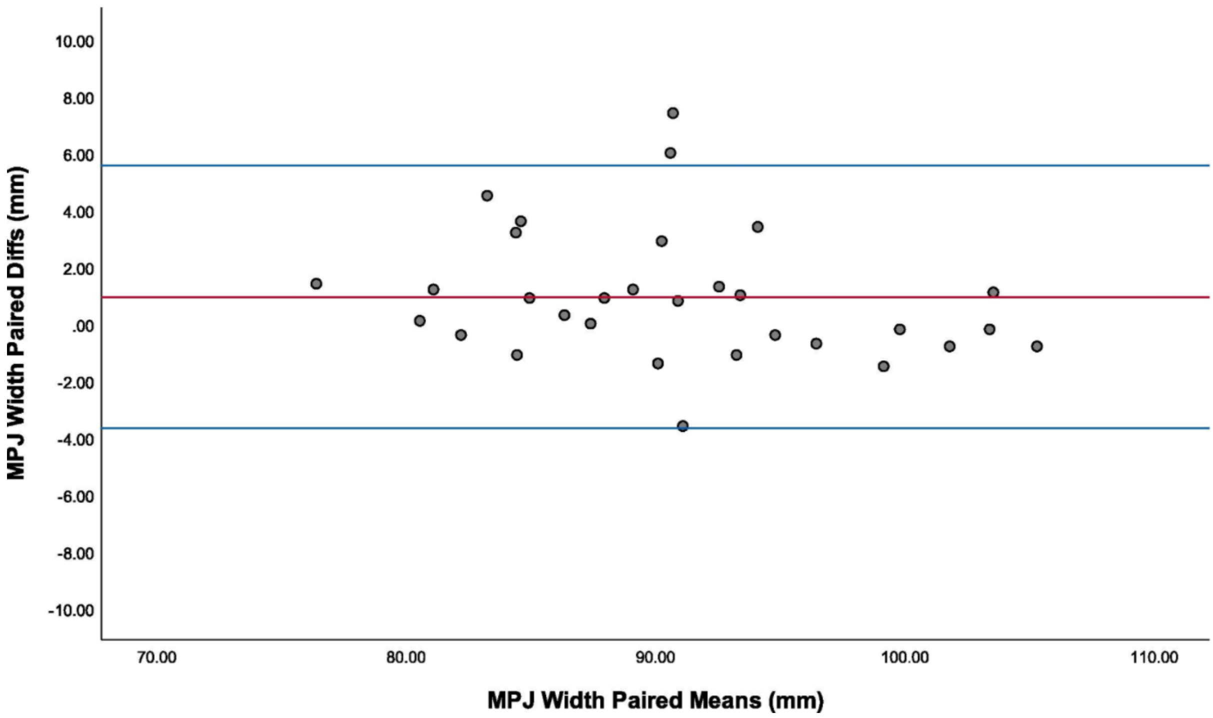


Fig. 9. 95% LOA graph for Rater 3 for MPJ Width repeated measurement (n = 30).

To support these findings of high reliability of the measurement method, further reliability analyses resulted in 95% ICCs ranging from 0.982 to 0.998 and 95% SEMs from 1.03 mm to 3.49 mm (Rater 3) across all repeated measurements (Tables 4 and 5).

Table 4. Intra-rater reliability analysis of Calc-A1 length measurements between three raters (n = 30).

| Measurement | ICC | 95% LOA Upper Lower | SEM (mm) | 95% SEM (mm) |
|---|---|---|---|---|
| Rater1: Calc-A1 Length Original v Repeat | 0.996 | 2.51–3.08 | 0.99 | 1.90 |
| Rater 2: Calc-A1 Length Original v Repeat | 0.998 | 1.74–1.59 | 0.55 | 1.08 |
| Rater 3: Calc-A1 Length Original v Repeat | 0.993 | 4.19–3.68 | 1.40 | 2.80 |

Table 5. Intra-rater reliability analysis of MPJ width measurements between three raters (n = 30).

| Measurement | ICC | 95% LOA Upper Lower | SEM (mm) | 95% SEM (mm) |
|---|---|---|---|---|
| Rater1: MPJ Width Original v Repeat | 0.982 | 2.39–3.15 | 0.99 | 1.94 |
| Rater 2: MPJ Width Original v Repeat | 0.995 | 1.58–1.58 | 0.53 | 1.03 |
| Rater 3: MPJ Width Original v Repeat | 0.945 | 6.93–2.31 | 1.74 | 3.49 |

## 4. Discussion

The Reel Method has previously demonstrated high statistical reliability and validity with bare footprint studies [11]. However, this reliability has not been evidenced with sock-clad footprints until the present study. Overall, the statistical analysis in this research demonstrated high reliability of the Reel Method among 3 raters. The data was found to be normally distributed, and measurements were consistent between and within raters. The agreement between and within all raters shows that the Reel Method is valid and reliable for the two-dimensional measurement of sock-clad footprints

The ICC calculated from a one-way ANOVA model allow for both random and fixed effects within the data. This can accurately reflect the consistency and agreement among and within raters. The 95% ICC ranges above 0.94 and 95% SEM absolute error ranges from 1.03 mm to 3.49 mm for all measurements across all raters in the context of a mean footprint length and width of 251.75 mm and 93.58 mm respectively demonstrate high reliability of this measurement method in sock-clad footprints Although good agreement was demonstrated by Rater 3 with respect to the repeated width measurements, the discrepancy in strength of agreement compared with Raters 1 and 2 reflects the practical difficulties in locating the anatomical landmarks for constructing this measurement.

Significantly, this study has important implications for footprint analysis in the forensic setting. In such situations, it may not be possible to determine if a discovered footprint was made from a bare or sock-clad foot, however, when this study is considered with the prior work of Reel et al. [11], the research finds that discerning whether a footprint was made by a sock-clad or bare foot is not a prerequisite for use of the Reel Method. This study also lends support to the findings of previous research by Nirenberg et al. that found there are no significant linear measurement differences between bare and sock-clad footprints using the Reel Method [26].

Rater 3 demonstrated the least agreement among raters, who was a novice at footprint analysis. Rater 3 was given all necessary information to perform the task and was trained by an experienced footprint analyst but was not given extensive training to minimize any interaction with the data. In contrast, Raters 1 and 2 were experienced in footprint analysis. The two were involved in forensic podiatry through membership in the American Society of Forensic Podiatry and forensic research; Rater 3 was not associated with any forensic association. This could further explain why the intra-rater reliability was higher in these two raters, as compared to Rater 3. Repeated practice has shown to improve performances in test-retest studies, which supports this theory [35]. This suggests those undertaking using the Reel method in the analysis of footprints require some mentorship and practice before embarking on casework. However, since this study showed high statistical reliability and good agreement using three different reliability tests for all measurements across all raters, inclusion of the novice participant’s results strengthens validity for the use of the Reel method for sock-clad footprints.

While the ICC and SEM have been shown to be the preferred methods for reliability testing, this study has limitations. First, the sex, weight, and height were not analysed separately; as such, it cannot be determined if these variables affected the SEM due to the presence of heteroscedasticity. These characteristics were considered for analysis with the Bland and Altman plot LOA for normal distribution, but a lack of individual analysis cannot definitively exclude this possibility [33].

The generalisability of the data to "real world" scenarios should be approached with caution; this study was done in a controlled data-collection environment with complete footprints, not partial footprints, and examined footprints from persons without visible foot deformities. Further research may explore the application of the Reel Method on partial footprints and for persons with foot deformities.

**5. Conclusion**

Scientists, forensic experts and podiatrists—especially forensic podiatrists—have applied a wide range of differing measurement techniques for analysis of footprints. In light of this, the authors' research focused on confirming the Reel Method as a two-dimensional measurement approach for both bare and sock-clad footprints.

The authors found the Reel Method demonstrated high reliability and validity with the two-dimensional measurement of sock-clad footprint. Using several statistical analysis techniques, the triangulation of the ICC, SEM, and LOA allowed for a more definitive picture of reliability, which supported the study's conclusions. The authors believe that this research contributes to validating the Reel Method as a two-dimensional measurement of sock-clad footprints.

**Human rights and Informed consent statement**

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1964 and its later amendments. Informed consent of all participants/subjects was obtained.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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