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Test-Retest Reliability of Sole Morphology Measurements Using a Novel Single-Image-Based Pin-Array Impression Reconstruction Method

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Featured Application: A novel method for three-dimensional sole morphological measurements gives high intra-rater, inter-rater, and inter-session reliability regardless of the rater's experience or time of measurement, and will be useful for foot assessment and subsequent applications, such as design and manufacture of customized orthoses or shoes.

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Abstract: Background: Assessment of the sole morphology provides a clinically useful measure of the foot condition, but existing methods are mostly limited to two-dimensional or non-weight-bearing conditions. The current study aimed to assess the reliability of a novel method called Single-Image-Based Pin-Array Impression Reconstruction Method (SIBPAIR) implemented on a commercial foot assessment system, and the intra-rater, inter-rater and inter-session reliability of the SIBPAIR-based protocol for three-dimensional sole morphological measurements. **Methods:** The reliability of the SIBPAIR method, and the intra-rater, inter-rater, and inter-session reliability of the SIBPAIR-based protocol in measuring morphological parameters of the sole were assessed by repeated measurements of fifteen young healthy adults by two male physical therapists, in terms of intra-class correlation coefficients (ICC) and standard error of measurement (SEM). **Results and Conclusions:** The SIBPAIR method was found to have very high reliability with very small SEM values, and the SIBPAIR-based protocol also showed very high intra-rater, inter-rater, and inter-session reliability with small SEM. These results indicate that accurate and reliable measurements could be obtained by following the protocol regardless of the rater's experience or time of measurement. This will be useful for foot assessment and subsequent applications, such as design and manufacture of customized orthoses or shoes.

Keywords: repeatability; foot morphology; foot scan; arch height; arch index

1. Introduction

The foot is one of the most complex anatomical structures in the human body, playing an important role in the normal function of the lower extremities [1]. The foot adapts to various terrains, and provides support and mobility necessary for standing and walking while bearing the body weight. This is accomplished by means of complex mechanical coordination between the highly loaded force-bearing structures of the foot/ankle complex, including the bones, muscles, ligaments, and articular surfaces. Therefore, any injuries or deformities of any of the force-bearing structures will affect the coordination, and thus the normal function of the complex. Since the bony structures provide kinematic links and attachments for the soft tissues, which in turn help maintain the dynamic alignment of the bones, morphological changes, or malalignment of the relevant bones will also affect the normal mechanical environment of the complex, leading to increased risk of injuries [2–6]. Foot structure problems have been shown to have a prevalence of 46% to 80% in clinical practice [7,8]. Maintaining a normal morphology and bony alignment is essential for the prevention of relevant injuries.

Assessment of the sole morphology provides a clinically useful measure of the condition of the bony alignment and force-bearing structures. Several parameters quantifying the sole morphology have been proposed and used in the literature and clinical practice, such as foot length (FL) [9], foot width (FW) [10], arch height (AH), normalized arch height (NAH), arch index (AI) [11], Staheli's arch index (SAI) [12], Chippaux–Smirak index (CSI) [13], hallux valgus angle (HVA) [14], minimal distance between hallux and other toes, great toe height, and instep height, etc. [15,16]. Among these parameters, those related to the medial longitudinal arch have received much research attention because the medial longitudinal arch is one of the most important features of the foot structure, relating to the absorption of ground forces and propulsion. The height of the medial longitudinal arch provides a direct measure of the foot morphology and function, and has been used to classify foot morphology into various types of normal-arched, low-arched, and high-arched feet. Abnormal arch height will compromise the load transmission and weight-bearing capabilities of the tarsal bones, increasing the risk of injuries of the ankle complex [17,18]. While the sole surface geometry and the medial arch height are three-dimensional in nature, the relevant measurement has been limited to two-dimensional or non-weight-bearing conditions. This is primarily because 3D measurement of the sole morphology under weight-bearing conditions is technically challenging, if not impossible [19].

Most existing clinical assessments of the medial arch morphology and arch height are based on 2D footprint or pressure distributions, which are easy and convenient to perform, but cannot measure directly the vertical dimensions, such as arch height [20]. In addition, the accuracy is limited as the arch morphology is 3D in nature, and the assessment is often affected by the experience of therapists or physicians (i.e., raters) [21–23]. Several attempts to predict 3D arch morphological parameters using a 2D footprint or planter pressure distribution have been reported in the literature. For example, a multivariate (5–6 variables) model based on plantar pressure parameters has been shown to predict only about 60% of the variability of the static arch height [24,25]. Other studies found no or moderate correlation between sub-areas of the plantar pressure area of the foot and common foot parameters, such as foot posture index, calcaneal pitch, metatarsal angle, and talocalcaneal angle [26]. The results of these studies suggest that features from the static or dynamic planar pressure distribution failed to predict the three-dimensional (3D) foot morphological parameters, especially the arch height.

With the advance of 3D scanning technology, it is possible to use 3D scanners to scan the shape of the foot [20,27–31]. Three major types of 3D scanning methods have been developed and used for body shape reconstruction, namely laser sensors [27,28,30], depth sensors [31,32], and photogrammetry [20,29,33]. However, for the measurement of the foot, a major limitation of the existing 3D scanning methods is that it only works during non-weight-bearing conditions because the sole of the foot cannot be measured when it is in contact with the floor under weight-bearing conditions. Standing on a glass platform may allow the measurement of sole morphology using 3D scanning sensors under the glass [31,32,34]. However, slight movement of the foot under weight-bearing conditions or image distortion owing to the refraction of the light through the glass during scanning may affect the accuracy of the measurements. Special calibration of measurements for these conditions will be needed to improve the accuracy. Another limitation is that these methods may not be applicable to measurements of alignment-corrected feet as the hands of the therapist may interfere with the measurement. Recently, a novel Single-Image-Based Pin-Array Impression Reconstruction Method (SIBPAIR) was developed for sole morphology measurements based on a commercially available foot assessment system (FAST, Enford International Co., Taiwan) (Figure 1). It provides a tool that overcomes the limitations of the existing methods in measuring the three-dimensional surface of the sole, enabling the measurement of the associated morphological parameters under partial or full weight-bearing conditions. However, the reliability of the novel approach has not yet been established.

Figure 1. The Single-Image-Based Pin-Array Impression Reconstruction (SIBPAIR) method implemented on a commercial 3D foot assessment system (FAST, Enford International Co., Taiwan): (**A**) measurement of the foot impression, and (**B**) reconstruction of the 3D sole surface for the subsequent calculation of foot morphological parameters.

The aim of the current study was to assess the intra-rater, inter-rater, and inter-session reliability of the overall protocol using the SIBPAIR method for measuring foot morphological parameters related to the classification of the foot types based on the medial longitudinal arch morphology, namely FL, FW, AI, CSI, SAI, AH, NAH, and HVA, in terms of intraclass correlation coefficients (ICC). The reliability of the SIBPAIR method itself was also assessed in terms of the reproducibility of the measured morphological parameters for a set of given foot sole impressions. It was also hypothesized that there would be no significant differences between raters or between sessions for any of the measured morphological parameters.

2. Materials and Methods

2.1. Subjects

Fifteen young adults (7 females, 8 males; 30 feet; age: 24.7 ± 1.3 years, height: 166.1 ± 8.6 cm, body mass: 58.3 ± 10.3 kg) and two male physical therapists (one with two years of experience in foot assessment and one with ten years of experience) participated in the current study as subjects and raters, respectively, giving informed written consent as approved by the Institutional Research Board. The two physical therapists were selected from a group of ten senior therapists (with over ten years extensive clinical experience in foot assessment) and a group of ten junior therapists (with less than two years clinical experience of foot assessment), respectively, as typical members representative of their corresponding groups. This type of experimental design has been used in several previous test-retest reliability studies [35–37]. Subjects were excluded if they had foot deformities or histories of neuromuscular injuries or disorders of the lower extremities that affect gait or posture. An a priori power analysis for one-way repeated measurement analysis of variance (ANOVA) for the comparison of the morphological parameters between trials, between raters and between sessions based on pilot results using G-power [38] determined that a projected sample size of 23 feet would be needed with a power of 0.8 and a large effect size (Cohen's d = 0.8) at a significance level of 0.05. Thus, a sample size of 30 feet was considered adequate for the main objectives of the current study.

2.2. Single-Image-Based Pin-Array Impression Reconstruction Method (SIBPAIR)

The three-dimensional (3D) morphology of the sole of the tested foot was measured using a novel method called Single-Image-Based Pin-Array Impression Reconstruction Method (SIBPAIR) implemented on a commercial foot assessment system (FAST, Enford International Co., Taiwan, Figure 1) [39]. The machine is 55.2 cm × 30.1 cm × 30.1 cm in length, width, and height, respectively, and has 2129 color-coded (green, red and white) pins (diameter: 3 mm) allocated in a measurement area (30 cm × 12 cm) with a maximum measurement depth of 35 mm. According to the manufacturer, the machine has a high 3D surface reconstruction accuracy with a bias of 0.06 mm and a precision of 0.35 mm, as well as a high surface reconstruction reliability (ICC > 0.98). Each subject stood on the machine with the tested foot placed on the measurement area, with the longitudinal axis of the foot connecting the tip of the second metatarsal head and the heel tip parallel to the measurement area, pressing the probe pins downwards to form a 3D impression of the foot. The position of the pins could be locked and maintained firmly by a uni-axis fast locking mechanism. A single image (2048 × 1536 pixels) of the impression was then taken using a tablet (Zenpad 8.0, ASUS, Taiwan; OS: Android 7.0), which was supported by a 37 cm movable tablet-supporting arm affixed to the machine, and oriented at an angle of about 20 degrees relative to the horizontal. These spatial parameters were chosen to optimize the accuracy of the 3D measurements, according to the manufacturer. A calibration image without a foot impression is also needed for the subsequent image analyses and 3D reconstruction. The SIBPAIR Method identifies the color-coded pins that are at known positions on the calibration image to define the local coordinate system of the measurement area of the FAST machine, along with the intrinsic and extrinsic parameters of the camera of the tablet, using Tsai's method [40]. With the parameters of the camera, the SIBPAIR method reconstructs the 3D surface of the foot impression by the following steps: (1) identifies the 2D coordinates of the color-coded pins on the image of the impression; (2) reconstructs the 3D coordinates of the pins using the camera parameters, 2D positions of the pins, as well as the known physical distribution of the pins in the measurement area; (3) calculates the morphological parameters of the sole from the reconstructed 3D surface.

2.3. Measurement Protocol Using SIBPAIR

Before foot sole measurement, each subject was asked to stand naturally with their feet shoulder-width apart while the toe-out angles of both feet were measured. The subject then stood with the tested foot placed on the measurement area of the FAST machine with the longitudinal axes of the foot and the measurement area parallel to each other, while the other foot was placed on a platform at the same height as the measurement surface. The rater made sure that the subject stood with the same toe-out angles and stance width as they had on the ground by guiding the subject to change the position and direction of the foot on the platform, and shifting the body weight between the feet until reaching a comfortable natural posture that approximated a relaxed 50% weight-bearing position as recommend by international standards for foot measurements (ISO 7250-1:2017) [41]. During the test, the probe pins in contact with the sole of the foot were displaced to form a negative of the sole surface, and their positions were locked by the locking mechanism. The subject removed the tested foot and a photograph of the 3D impression was taken using the tablet system at the predefined position supported by the rotating arm. The image was then used to reconstruct the 3D surface of the sole using the SIBPAIR method, and the morphological parameters were obtained.

2.4. Repeated Measurements

The evaluation of the reliability of the foot sole measurement using the SIBPAIR method consisted of two parts: the SIBPAIR method alone, and the SIBPAIR-based measurement protocol. For the reliability of the SIBPAIR method alone, each subject left his/her foot impression on the measurement area with the assistance of the senior rater, and the foot impression was then photographed and analyzed five times. The tablet was moved away from the measurement position after each measurement. For the assessment of the intra-rater and inter-rater reliability of the overall measurement protocol, each subject was assessed separately by the two raters in a random order following the measurement procedure described above. Each foot was assessed by each rater five times (trials), giving five sole impressions, and each impression was measured five times. A 30-min break was allowed between assessments by the two raters. A re-test session was performed at least 24 h after the first session following the same test protocol to assess the inter-session reliability [35,36].

2.5. Morphological Parameters of the Sole

Eight parameters describing the morphology of the sole of the foot, particularly those related to the classification of the foot types based on the medial longitudinal arch morphology, were considered in the current study, and were obtained from the 3D surface of the sole reconstructed using the SIBPAIR method with the FAST system, namely FL, FW, HVA, AI, SAI, CSI, AH, and NAH (Figure 2). The FL was defined as the horizontal distance from the most anterior point of the foot to the most posterior point of the foot, projected onto the longitudinal axis of the foot, defined as the line joining the tip of the second distal phalange and the most posterior projection of the calcaneus. The FW was defined as the horizontal distance perpendicular to the longitudinal axis between the most medial prominence of the head of the first metatarsal and the most lateral prominence of the fifth metatarsal. The HVA was defined as the angle formed by the vertical planes best fitting the medial surfaces of the hallux and the foot (Figure 2). Three parameters for quantifying the medial longitudinal arch based on the 2D footprint were considered in the current study. They were obtained from the horizontal projection of the measured 3D surface model of the sole. The AI was calculated as the ratio of the areas of the horizontal projections of the mid foot (part B) and the foot (parts A + B + C) (Figure 2) [11]; SAI was the ratio of the widths of the midfoot and heel (b/a, Figure 2) [12]; and the CSI was the ratio of the widths of the midfoot and the metatarsals (b/c, Figure 2) [13]. In contrast to the above parameters in the horizontal plane (or, footprint), the AH and NAH were obtained from the vertical projection of the measured 3D surface model of the sole. The AH was the maximum height of the longitudinal arch on the vertical plane passing through the medial borders of the calcaneus and the first metatarsal, which further defined the NAH when divided by the truncated foot length (TFL) (Figure 2) [17]

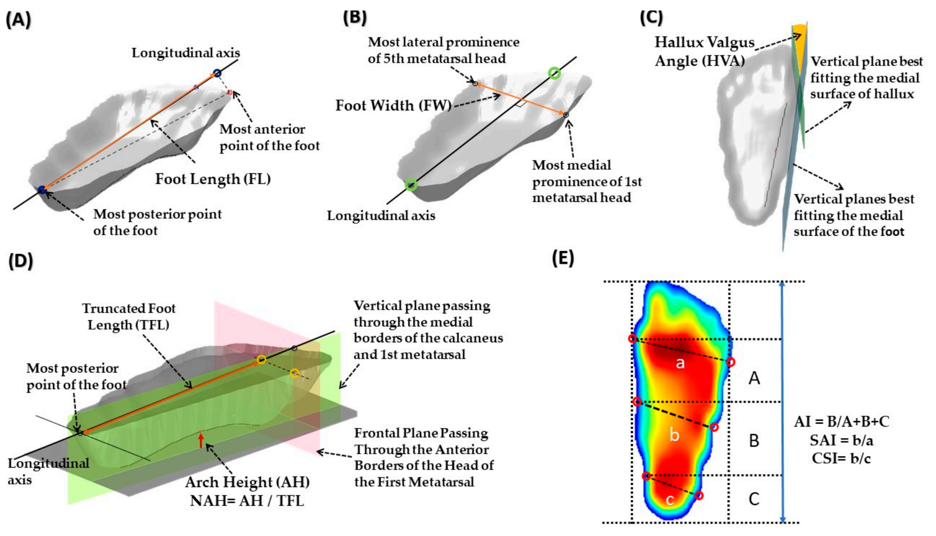

Figure 2. Schematic illustration of the definitions of the foot parameters based on the measured 3D sole surface: (**A**) foot length (FL); (**B**) foot width (FW); (**C**) hallux valgus angle (HVA); (**D**) arch height (AH) and normalized arch height (NAH). (**E**) Arch index (AI), Staheli's arch index (SAI), and Chippaux-Smirak index (CSI). (This figure is best viewed in color).

2.6. Statistical Analysis

Comparisons of the morphological parameters between the measurements of the five trials of the SIBPAIR method were performed using one-way repeated measurement analysis of variance (ANOVA), while comparisons of measurements between raters (senior vs. junior rater) and sessions (session 1 vs. session 2) were performed using a one-way repeated measurement ANOVA. Reliability of these measurements was assessed in terms of intraclass correlation coefficients (ICC) using a one-way random-effects model (ICC1,k) for the SIBPAIR method, a two-way mixed-effects model (ICC3,1) for intra-rater assessments, and a two-way random-effects model (ICC2,k) for inter-rater assessments, while a two-way mixed-effects model (ICC3,k) was used for inter-session reliability [42,43]. The values of ICC indicated high (0.81–1.00), good (0.61–0.80), moderate (0.41–0.60), fair (0.21–0.40), and poor (below 0.20) reliability, respectively [44]. The standard error of measurement (SEM) was also used to quantify the reproducibility of an assessment for the SIBPAIR method and the raters. The SEM is an index of the precision of the measurements in the units of the measured quantity, and was calculated using the square root of the within-subject variance ($SEM = s \cdot \sqrt{1-r}$; s is the standard deviation of the measurements and r is the ICC). A statistical significance of 0.05 was set for all analyses. All statistical analyses were performed using a statistical software package (SPSS v.21; SPSS Inc., Chicago, IL, USA).

3. Results

No significant between-trial differences were found for any parameters measured using the SIBPAIR method ($p > 0.05$, Table 1). No interactions between rater and session factors were found.

Table 1. Means (standard deviations, SD) of the measured foot parameters for each of the five trials, as well as the ICC values for the reliability of repeated measurements of the SIBPAIR method (n = 30).

Trial	FL (mm)	FW (mm)	AI	SAI	CSI (%)	AH (mm)	NAH	HVA (Degree)
1	254.5 (12.2)	103.5 (6.3)	0.30 (0.05)	1.02 (0.25)	54.8 (15.1)	96.6 (38.8)	0.05 (0.02)	9.9 (4.7)
2	254.6 (12.2)	103.4 (6.1)	0.30 (0.05)	1.02 (0.24)	54.8 (15.4)	96.4 (38.4)	0.05 (0.02)	10.0 (4.6)
3	254.6 (12.1)	103.5 (6.1)	0.30 (0.05)	1.02 (0.24)	54.9 (15.7)	96.0 (38.1)	0.05 (0.02)	10.2 (4.7)
4	254.6 (12.2)	103.3 (6.1)	0.30 (0.05)	1.02 (0.26)	54.1 (15.9)	97.5 (39.3)	0.05 (0.02)	10.1 (4.5)
5	254.8 (12.4)	103.3 (6.1)	0.30 (0.05)	1.02 (0.24)	54.2 (15.9)	96.1 (39.1)	0.05 (0.02)	10.0 (4.4)
p-value	0.29	0.73	0.48	0.08	0.16	0.537	0.553	0.054
ICC	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.99
SEM	0.85	0.43	0.003	0.002	1.10	2.7	0.001	0.32

The SIBPAIR method showed a very high level of reliability of repeated measurements for all foot parameters (ICC > 0.98) (Table 1). Very high intra-rater reliability was also found for all foot parameters measured by both raters following the measurement protocol (ICC > 0.84; ICC = 0.84 for SAI and HVA; Table 2). No significant rater or session effects were found for any foot parameters ($p > 0.05$, Tables 3 and 4). Very high inter-rater (ICC > 0.96) and inter-session (ICC > 0.86) reliability were also found for the measurement protocol for all foot parameters (Tables 3 and 4).

Table 2. Means (standard deviations, SD) of foot parameters for each of the five trials by the senior and junior raters. ICC values for intra-rater reliability of the repeated measurements are also given (n = 30).

	Trial	FL (mm)	FW (mm)	AI	SAI	CSI (%)	AH (mm)	NAH	HVA (Degree)
					Senior rater				
	1	253.8 (13.1)	101.3 (5.9)	0.30 (0.04)	1.03 (0.25)	52.1 (16.4)	96.7 (41.9)	0.05 (0.02)	11.0 (4.8)
	2	254.5 (12.6)	102.6 (5.6)	0.30 (0.04)	1.01 (0.21)	53.7 (16.1)	97.8 (46.8)	0.05 (0.02)	10.8 (5.0)
	3	253.2 (11.7)	101.8 (5.6)	0.30 (0.04)	1.01 (0.22)	54.7 (15.5)	98.5 (46.2)	0.05 (0.02)	10.3 (4.7)
	4	254.8 (12.9)	101.7 (5.4)	0.30 (0.04)	1.04 (0.23)	54.9 (15.1)	96.4 (47.5)	0.04 (0.02)	10.6 (4.9)
	5	253.7 (12.4)	101.5 (5.9)	0.30 (0.04)	1.03 (0.21)	55.8 (15.0)	93.5 (47.3)	0.04 (0.02)	10.5 (4.7)
p-value		0.07	0.06	0.382	0.515	0.051	0.457	0.236	0.627
ICC		0.96	0.91	0.9	0.86	0.91	0.9	0.9	0.86
SEM		1.75	1.19	0.009	0.006	3.28	10.1	0.005	1.25
					Junior rater				
	1	254.3 (13.3)	103.4 (5.9)	0.30 (0.04)	1.05 (0.21)	55.9 (14.8)	88.8 (38.6)	0.04 (0.02)	10.8 (5.3)
	2	253.9 (13.1)	103.1 (5.5)	0.30 (0.04)	1.04 (0.23)	53.7 (13.0)	96.4 (42.2)	0.05 (0.02)	9.9 (4.7)
	3	254.5 (13.8)	103.3 (6.2)	0.30 (0.04)	1.05 (0.23)	56.8 (15.0)	93.4 (40.4)	0.04 (0.02)	10.3 (5.00)
	4	254.2 (12.6)	102.9 (6.00)	0.30 (0.04)	1.01 (0.21)	54.8 (16.3)	91.5 (37.7)	0.04 (0.02)	10.4 (5.9)
	5	254.4 (13.3)	102.7 (5.8)	0.30 (0.04)	1.02 (0.20)	54.7 (15.9)	94.7 (39.2)	0.05 (0.02)	10.1 (4.5)
p-value		0.89	0.60	0.23	0.30	0.20	0.11	0.40	0.48
ICC		0.97	0.91	0.91	0.84	0.87	0.92	0.9	0.84
SEM		1.59	1.43	0.008	0.006	3.78	7.8	0.004	1.43

Table 3. Means (standard deviations, SD) of the foot parameters, as well as inter-rater ICC and SEM (n = 30).

Foot Parameters	Session	Mean (SD)	ICC	SEM	*p*-Value
FL (mm)	Senior Junior	254.0 (12.1) 254.3 (12.8)	0.98	2.54	0.65
FW (mm)	Senior Junior	101.8 (5.2) 103.1 (5.1)	0.90	2.51	0.55
AI	Senior Junior	0.30 (0.04) 0.30 (0.04)	0.92	0.01	0.91
SAI	Senior Junior	1.02 (0.2) 1.03 (0.2)	0.91	0.08	0.91
CSI (%)	Senior Junior	54.2 (15.0) 55.1 (14.3)	0.92	5.9	0.60
AH (mm)	Senior Junior	96.6 (43.2) 92.9 (37.6)	0.99	5.4	0.74
NAH	Senior Junior	0.05 (0.02) 0.05 (0.02)	0.99	0.003	0.79
HVA (degrees)	Senior Junior	10.5 (4.3) 10.3 (4.5)	0.88	2.3	0.23

The SEM values for the SIBPAIR method were 0.85 mm, 0.43 mm, 0.31°, 2.7 mm, and 0.001 for FL, FW and HVA, AH, and NAH, respectively (Table 1). Those for AI, SAI, and CSI were 0.003, 0.002, and 1.10%, respectively (Table 1). When the experimental protocol was used, the SEM values were slightly increased. For the senior rater the SEM were 1.75 mm, 1.19 mm, 1.25°, 10.1 mm, and 0.005 for FL, FW and HVA, AH, and NAH, respectively (Table 2). Those for AI, SAI and CSI were 0.009, 0.006, and 3.28%, respectively (Table 2).

The corresponding values for the junior rater were 1.59 mm, 1.43 mm, 1.43°, 7.8 mm, 0.004, 0.008, 0.006, and 3.78%, respectively (Table 2).

Table 4. Means (standard deviations, SD) of the foot parameters, as well as inter-session ICC and SEM (n = 30).

Foot Parameters	Session	Mean (SD)	ICC	SEM	*p*-Value
FL (mm)	First Second	255.4 (13.3) 254.2 (12.7)	0.98	2.6	0.82
FW (mm)	First Second	102.5 (5.1) 102.4 (5.0)	0.91	2.2	0.74
AI	First Second	0.30 (0.04) 0.30 (0.04)	0.91	0.01	0.55
SAI	First Second	1.03 (0.23) 1.04 (0.21)	0.90	0.08	0.57
CSI	First Second	55.5 (14.0) 55.4 (15.2)	0.91	6.4	0.49
AH (mm)	First Second	97.2 (42.2) 96.0 (41.8)	0.97	10.4	0.65
NAH	First Second	0.04 (0.02) 0.04 (0.02)	0.94	0.007	0.95
HVA (degrees)	First Second	10.8 (4.4) 10.9 (4.0)	0.86	2.2	0.19

The SEM values for the inter-rater measurements were 2.54 mm, 2.51 mm, 2.30°, 5.4 mm, 0.003, 0.01, 0.08, and 5.9% for FL, FW and HVA, AH and NAH, AI, SAI, and CSI, respectively (Table 3). The corresponding values for inter-session measurements were 2.58 mm, 2.23 mm, 2.20°, 10.4 mm, 0.007, 0.01, 0.08, and 6.4%, respectively (Table 4).

4. Discussion

The current study aimed to assess the reliability of the novel SIBPAIR method, and the intra-rater, inter-rater, and inter-session reliability of the overall SIBPAIR-based measurement protocol for foot morphological parameters, in terms of ICC and SEM. The SIBPAIR method was found to have very high reliability with very small SEM values (Table 1). The overall SIBPAIR-based measurement protocol was also shown to have very high intra-rater, inter-rater, and inter-session reliability with small SEM. The current results indicate that following the experimental protocol the SIBPAIR method implemented on the FAST machine was capable of producing accurate and reliable measurements regardless of the rater's experience or time of measurement. These outcomes will be useful for foot assessment and subsequent applications, such as design and manufacture of customized orthoses or shoes.

The SIBPAIR method identifies the 2D coordinates of the color-coded pins on the image of the impression. These coordinates are then combined with the camera parameters and the known physical distribution of the pins in the measurement area to reconstruct the 3D coordinates of the pins, and thus the 3D surface of the foot sole. Given a foot impression, the SIBPAIR method showed a very high reliability with ICC values greater than 0.95, indicating that the 2D image analysis, the 3D surface reconstruction, and the morphological parameters calculated were highly repeatable when the measurement image was taken at different poses within a range allowed by the movable tablet-supporting arm. The SIBPAIR method also showed low SEM values for the morphological parameters measured, without significant differences between trials. Standard error of measurement is a measure of how much the measurements are spread around the "true" outcome. The high ICC and low SEM suggest that the SIBPAIR method is a reliable and accurate method for foot morphological measurements, and that the repeatability of the outcome measurements in real-life applications will require using the measurement protocol involving the subject positioning and rater operation.

Following the measurement protocol, the SIBPAIR method showed high intra-rater, inter-rater, and inter-session reliability with ICC values greater than 0.90 and low SEM, indicating that rater experience and time of measurement did not affect the reliability of the measurement of most morphological parameters. These results were much better than those from most previously published methods, especially for parameters that are 3D in nature and not directly defined on 2D footprint or pressure distributions. For example, AH and NAH measured using scales were reported to have moderate (ICC = 0.565 and 0.563) to high (ICC = 0.71) reliability [17,45]. In the current study, the HVA was the only parameter with an ICC slightly less than 0.90 (ICC > 0.84). These results indicate that the SIBPAIR method has high reliability for studies of groups of patients in a clinical trial, and is also acceptable for assessment of individuals, except for the HVA. As suggested by Fitzpatrick et al. (1998), an ICC of 0.90 may be considered the minimum level acceptable to be used in individuals [46]. The relatively reduced reliability in HVA seems to be a common issue among measurement methods, as previous studies also reported relatively low reliability for this parameter [17]. Other studies reported low to moderate reliability for HVA. Use of goniometry, for instance, had moderate values (ICC = 0.81) [47], whereas footprint analysis for the foot angle (not specifically HVA) showed low ICC values (0.33–0.78) [48]. The reliability of the SIBPAIR-based measurement protocol for HVA was comparable to that using X-ray imaging (ICC = 0.89) and very close to the minimum level of 0.9 for use in individuals, indicating a significant improvement over most existing non-ionizing measurement methods.

For parameters that were directly defined based on 2D footprint or pressure distributions in the literature, namely the three arch indices (AI, SAI, and CSI), the current approach results also gave high intra-rater, inter-rater, and inter-session reliability with ICC values greater than 0.90 and low SEM. These results were comparable with most previously published methods and were even better than some methods. The AI measured using footprints and plantar pressure distributions was reported to have high intra-rater (ICC = 0.96–0.99) and inter-session (ICC = 0.94) reliability [11,49,50], while high intra-rater (ICC = 0.96) and moderate inter-rater (ICC = 0.80) reliability was reported for SAI [51,52], and the corresponding ICC values for the CSI were 0.99 and 0.79, respectively [51]. These previous studies showed that based on pressure platform and footprint data, AI could be a highly reliable parameter, but the SAI and CSI were only moderately reliable when measured by different raters, and tended to be underestimated [51]. The current results show that the SIBPAIR-based method overcomes the limitations of existing methods based on footprint or plantar pressure, achieving high measurement reliability for all the sole parameters considered in the current study.

The current study reports the test-retest reliability of a new experimental protocol based on the SIBPAIR method implemented on the FAST machine. The results showed that the new method was capable of giving accurate and reliable measurements regardless of the rater's experience or time of measurement. It will be useful for foot assessment and subsequent applications, such as design and manufacture of customized orthoses or shoes. It may also be useful for the study of morphological differences between dominant and non-dominate feet. The current study was limited to normal foot morphology. Further studies may include a reliability assessment on subjects with a greater range of foot deformities, e.g., severe hallux varus, clubfoot, etc. Given the high reliability and low SEM for most of the parameters, a direct validation of the measurements against measurements made by using medical images will be needed for future applications that required accurate data for decision-making, such as in a clinical setting. Further studies may also include more parameters based on the reconstructed weight-bearing 3D sole surface measured by the current approach, such as the distances of the first and fifth metatarsophalangeal joints to the sustentaculum tali, great toe height, distal end of the first toe and instep height [15,16,53,54], and may determine their test-retest reliabilities. One senior and one junior rater were used in the current study following previous protocols [35–37]. Further studies may include raters with different levels of experience for a more complete assessment of the effects of rater experience.

5. Conclusions

The current study shows that the SIBPAIR method had both high instrument and test protocol reliabilities in reconstructing the three-dimensional foot sole surface and measuring foot parameters. The current results indicate that by following the experimental protocol the SIBPAIR method implemented on the FAST machine was capable of producing accurate and reliable measurements regardless of the rater's experience or time of measurement. This will be useful for foot assessment and subsequent applications, such as design and manufacture of customized orthoses or shoes.

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Abbreviations

2D	two-dimensional
3D	three-dimensional
AI	arch index
AH	arch height
ANOVA	analysis of variance
CSI	Chippaux-Smirak index
FL	foot length
FW	foot width
HVA	hallux valgus angle
ICC	intra-class correlation coefficients
NAH	normalized arch height
SIBPAIR	single-image-based pin-array impression reconstruction method
SAI	Staheli's arch index
SEM	standard error of measurement

References

1. Wu, S.-K.; You, J.-Y.; Chen, H.-Y.; Lou, S.-Z. Gastrocnemius tightness affects hip and pelvic movement in gait. *Biomed. Eng. Appl. Basis Commun.* **2020**, *32*, 2050031. [CrossRef]
2. Clement, D.B.; Taunton, J.E.; Smart, G.W.; McNicol, K.L. A Survey of Overuse Running Injuries. *Physician Sportsmed.* **1981**, *9*, 47–58. [CrossRef] [PubMed]
3. Gross, M.T. Chronic Tendinitis: Pathomechanics of Injury, Factors Affecting the Healing Response, and Treatment. *J. Orthop. Sports Phys. Ther.* **1992**, *16*, 248–261. [CrossRef]
4. Hamill, J.; Bates, B.T.; Holt, K.G. Timing of lower extremity joint actions during treadmill running. *Med. Sci. Sports Exerc.* **1992**, *24*, 808–813. [CrossRef]
5. McClay, I.; Manal, K. Coupling parameters in runners who pronate and normals. *J. Appl. Biomech.* **1996**, *13*, 107–124.

6. Subotnick, S.I. The biomechanics of running implications for the prevention of foot injuries. *Sports Med.* **1985**, *2*, 144–153. [CrossRef] [PubMed]
7. Abegaz, B.A.; Awoke, D.G. Factors affecting foot arch development in Northern Ethiopia. *Anatomy* **2017**, *11*, 26–29. [CrossRef]
8. Pauk, J.; Ezerskiy, V.; Raso, J.V.; Rogalski, M. Epidemiologic Factors Affecting Plantar Arch Development in Children with Flat Feet. *J. Am. Podiatr. Med. Assoc.* **2012**, *102*, 114–121. [CrossRef]
9. Yu, C.-Y.; Tu, H.-H. Foot surface area database and estimation formula. *Appl. Ergon.* **2009**, *40*, 767–774. [CrossRef]
10. Mauch, M.; Grau, S.; Krauss, I.; Maiwald, C.; Horstmann, T. Foot morphology of normal, underweight and overweight children. *Int. J. Obes.* **2008**, *32*, 1068–1075. [CrossRef]
11. Cavanagh, P.R.; Rodgers, M.M. The arch index: A useful measure from footprints. *J. Biomech.* **1987**, *20*, 547–551. [CrossRef]
12. Staheli, L.T.; Chew, D.E.; Corbett, M. The longitudinal arch. A survey of eight hundred and eighty-two feet in normal children and adults. *J. Bone Jt. Surg. Am. Vol.* **1987**, *69*, 426–428.
13. Forriol, F.; Pascual, J. Footprint Analysis between Three and Seventeen Years of Age. *Foot Ankle* **1990**, *11*, 101–104. [CrossRef] [PubMed]
14. Liang, Z.Q.; Meng, Y.; Popik, S.; Chen, F.F. Analysis of Foot Morphology in Habitually Barefoot Group. *J. Biomim. Biomater. Biomed. Eng.* **2019**, *41*, 1–9. [CrossRef]
15. Zhao, X.; Tsujimoto, T.; Kim, B.; Katayama, Y.; Tanaka, K. Characteristics of foot morphology and their relationship to gender, age, body mass index and bilateral asymmetry in Japanese adults. *J. Back Musculoskelet. Rehabil.* **2017**, *30*, 527–535. [CrossRef] [PubMed]
16. Tomassoni, D.; Traini, E.; Amenta, F. Gender and age related differences in foot morphology. *Maturitas* **2014**, *79*, 421–427. [CrossRef] [PubMed]
17. Williams, D.S.; McClay, I.S. Measurements Used to Characterize the Foot and the Medial Longitudinal Arch: Reliability and Validity. *Phys. Ther.* **2000**, *80*, 864–871. [CrossRef]
18. Queen, R.M.; Mall, N.A.; Hardaker, W.M.; Nunley, J.A. Describing the Medial Longitudinal Arch Using Footprint Indices and a Clinical Grading System. *Foot Ankle Int.* **2007**, *28*, 456–462. [CrossRef] [PubMed]
19. Caravaggi, P.; Pataky, T.; Goulermas, J.Y.; Savage, R.; Crompton, R. A dynamic model of the windlass mechanism of the foot: Evidence for early stance phase preloading of the plantar aponeurosis. *J. Exp. Biol.* **2009**, *212*, 2491–2499. [CrossRef]
20. Lee, Y.-C.; Wang, M.-J. Taiwanese adult foot shape classification using 3D scanning data. *Ergonomics* **2014**, *58*, 513–523. [CrossRef]
21. Kouchi, M.; Mochimaru, M.; Tsuzuki, K.; Yokoi, T. Interobserver errors in anthrofometry. *J. Hum. Ergol.* **1999**, *28*, 15–24.
22. Kouchi, M.; Mochimaru, M. Errors in landmarking and the evaluation of the accuracy of traditional and 3D anthropometry. *Appl. Ergon.* **2011**, *42*, 518–527. [CrossRef]
23. Cornwall, M.W.; McPoil, T.G.; Lebec, M.; Vicenzino, B.; Wilson, J. Reliability of the Modified Foot Posture Index. *J. Am. Podiatr. Med. Assoc.* **2008**, *98*, 7–13. [CrossRef] [PubMed]
24. Teyhen, D.S.; Stoltenberg, B.E.; Collinsworth, K.M.; Giesel, C.L.; Williams, D.G.; Kardouni, C.H.; Molloy, J.M.; Goffar, S.L.; Christie, D.S.; McPoil, T. Dynamic plantar pressure parameters associated with static arch height index during gait. *Clin. Biomech.* **2009**, *24*, 391–396. [CrossRef] [PubMed]
25. Teyhen, D.S.; Stoltenberg, B.E.; Eckard, T.G.; Doyle, P.M.; Boland, D.M.; Feldtmann, J.J.; McPoil, T.G.; Christie, D.S.; Molloy, J.M.; Goffar, S.L. Static Foot Posture Associated with Dynamic Plantar Pressure Parameters. *J. Orthop. Sports Phys. Ther.* **2011**, *41*, 100–107. [CrossRef] [PubMed]
26. Lee, J.S.; Kim, K.B.; Jeong, J.O.; Kwon, N.Y.; Jeong, S.M. Correlation of Foot Posture Index with Plantar Pressure and Radiographic Measurements in Pediatric Flatfoot. *Ann. Rehabil. Med.* **2015**, *39*, 10–17. [CrossRef]
27. Telfer, S.; Woodburn, J. The use of 3D surface scanning for the measurement and assessment of the human foot. *J. Foot Ankle Res.* **2010**, *3*, 19. [CrossRef] [PubMed]
28. Alcacer, A.; Epifanio, I.; Ibáñez, M.V.; Simó, A.; Ballester, A. A data-driven classification of 3D foot types by archetypal shapes based on landmarks. *PLoS ONE* **2020**, *15*, e0228016. [CrossRef]
29. Grazioso, S.; Caporaso, T.; Selvaggio, M.; Panariello, D.; Ruggiero, R.; Di Gironimo, G. Using photogrammetric 3D body reconstruction for the design of patient–tailored assistive devices. In Proceedings of the 2019 II Workshop on Metrology for Industry 4.0 and IoT (MetroInd4.0&IoT), Naples, Italy, 4–6 June 2019; pp. 240–242.
30. Redaelli, D.F.; Barsanti, S.G.; Biffi, E.; Storm, F.A.; Colombo, G. Comparison of geometrical accuracy of active devices for 3D orthopaedic reconstructions. *Int. J. Adv. Manuf. Technol.* **2021**, *114*, 1–24. [CrossRef]
31. Wang, M.; Wang, X.; Fan, Z.; Zhang, S.; Peng, C.; Liu, Z. A 3D foot shape feature parameter measurement algorithm based on Kinect. *EURASIP J. Image Video Process.* **2018**, *2018*, 119. [CrossRef]
32. Rogati, G.; Leardini, A.; Ortolani, M.; Caravaggi, P. Semi-automatic measurements of foot morphological parameters from 3D plantar foot scans. *J. Foot Ankle Res.* **2021**, *14*, 1–8. [CrossRef]
33. Chun, S.; Kong, S.; Mun, K.-R.; Kim, J. A Foot-Arch Parameter Measurement System Using a RGB-D Camera. *Sensors* **2017**, *17*, 1796. [CrossRef]
34. Chang, J.-H.; Wang, S.-H.; Kuo, C.-L.; Shen, H.C.; Hong, Y.-W.; Lin, L.-C. Prevalence of flexible flatfoot in Taiwanese school-aged children in relation to obesity, gender, and age. *Eur. J. Nucl. Med. Mol. Imaging* **2009**, *169*, 447–452. [CrossRef] [PubMed]
35. Evans, A.M.; Rome, K.; Peet, L. The foot posture index, ankle lunge test, Beighton scale and the lower limb assessment score in healthy children: A reliability study. *J. Foot Ankle Res.* **2012**, *5*, 1–6. [CrossRef] [PubMed]

36. Carroll, M.; Annabell, M.-E.; Rome, K. Reliability of capturing foot parameters using digital scanning and the neutral suspension casting technique. *J. Foot Ankle Res.* **2011**, *4*, 9. [CrossRef] [PubMed]
37. Lu, T.-W.; Hsu, H.-C.; Chang, L.-Y.; Chen, H.-L. Enhancing the examiner's resisting force improves the reliability of manual muscle strength measurements: Comparison of a new device with hand-held dynamometry. *Acta Derm. Venereol.* **2007**, *39*, 679–684. [CrossRef] [PubMed]
38. Erdfelder, E.; Faul, F.; Buchner, A. GPOWER: A general power analysis program. *Behav. Res. Methods Instrum. Comput.* **1996**, *28*, 1–11. [CrossRef]
39. Hsieh, C.-Y. Mold and Method for Getting Foot Model Thereof. U.S. Patent 10232577, 4 July 2019.
40. Tsai, R. A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses. *IEEE J. Robot. Autom.* **1987**, *3*, 323–344. [CrossRef]
41. ISO. *ISO 7250-1: 2017 Basic Human Body Measurements for Technological Design—Part 1: Body Measurement Definitions and Landmarks*; ISO: Geneva, Switzerland, 2017.
42. Koo, T.K.; Li, M.Y. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J. Chiropr. Med.* **2016**, *15*, 155–163. [CrossRef]
43. Shrout, P.E.; Fleiss, J.L. Intraclass correlations: Uses in assessing rater reliability. *Pol. Psychol. Bull.* **1979**, *86*, 420. [CrossRef]
44. Altman, D. Multiple regression. In *Practical Statistics for Medical Research*; Chapman and Hall/CRC: Boca Raton, FL, USA; London, UK, 1991; p. 349.
45. Hill, M.; Naemi, R.; Branthwaite, H.; Chockalingam, N. The relationship between arch height and foot length: Implications for size grading. *Appl. Ergon.* **2017**, *59*, 243–250. [CrossRef]
46. Fitzpatrick, R.; Davey, C.; Buxton, M.J.; Jones, D.R. Evaluating patient-based outcome measures for use in clinical trials. *Health Technol. Assess.* **1998**, *2*, 14. [CrossRef]
47. Janssen, D.M.; Sanders, A.P.; Guldemond, N.A.; Hermus, J.; Walenkamp, G.H.; Van Rhijn, L.W. A comparison of hallux valgus angles assessed with computerised plantar pressure measurements, clinical examination and radiography in patients with diabetes. *J. Foot Ankle Res.* **2014**, *7*, 1–9. [CrossRef]
48. Taranto, J.; Taranto, M.J.; Bryant, A.; Singer, K.P. Angle of gait: A comparative reliability study using footprints and the EMED-SF®. *Foot* **2005**, *15*, 7–13. [CrossRef]
49. Igbigbi, P.; Msamati, B. The footprint ratio as a predictor of pes planus: A study of indigenous Malawians. *J. Foot Ankle Surg.* **2002**, *41*, 394–397. [CrossRef]
50. Menz, H.B.; Munteanu, S.E. Validity of 3 Clinical Techniques for the Measurement of Static Foot Posture in Older People. *J. Orthop. Sports Phys. Ther.* **2005**, *35*, 479–486. [CrossRef] [PubMed]
51. Zuil-Escobar, J.C.; Martínez-Cepa, C.B.; Martín-Urrialde, J.A.; Gómez-Conesa, A. Reliability and Accuracy of Static Parameters Obtained from Ink and Pressure Platform Footprints. *J. Manip. Physiol. Ther.* **2016**, *39*, 510–517. [CrossRef]
52. Fascione, J.M.; Crews, R.T.; Wrobel, J.S. Dynamic footprint measurement collection technique and intrarater reliability: Ink mat, paper pedography, and electronic pedography. *J. Am. Podiatr. Med. Assoc.* **2012**, *102*, 130–138. [CrossRef]
53. Fantini, M.; Fantini, M.; De Crescenzio, F.; De Crescenzio, F.; Brognara, L.; Brognara, L.; Baldini, N.; Baldini, N. Design and Rapid Manufacturing of a customized foot orthosis: A first methodological study. In Proceedings of the 13th International Scientific Conference, Catania, Italy, 14–16 September 2017; pp. 457–467. [CrossRef]
54. Schrank, E.S.; Stanhope, S.J. Dimensional accuracy of ankle-foot orthoses constructed by rapid customization and manufactuing framework. *J. Rehabil. Res. Dev.* **2011**, *48*. [CrossRef]