ORIGINAL ARTICLE

Evaluation of Usability of the Tiger Full Foot 3D Scanner for the Measurements of Basic Foot Dimensions in Clinical Practice

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Background: Foot dimension information is important both for footwear design and clinical applications. In recent years, non-contact three-dimensional foot digitizers/scanners became popular as they are non-invasive and are both valid and reliable for the most of measures. Some of them also offer automated calculations of basic foot dimensions. The study aimed to determine test-retest reliability, objectivity, and concurrent validity of the Tiger full foot 3D scanner as well as the relationship between the manual measures of the medial longitudinal arch of the foot and its alternative parameters obtained automatically by the scanner.

Methods: Intraclass correlation coefficients and the values of minimal detectable change were used to assess the reliability and objectivity of the scanner. Concurrent validity and the relationship between the arch height measures were determined by the Pearson's correlation coefficient and the limits of agreement between the scanner and the calliper method.

Results: Both the relative and absolute agreement between the repeated measurements obtained by the scanner show excellent reliability and objectivity of linear measures and only good to nearly good test-retest reliability and objectivity of the arch height. Correlations between the values obtained by the scanner and the calliper were generally higher in linear measures ($r_p \geq 0.929$). The representativeness of state of bony architecture by the soft tissue margin of the medial foot arch demonstrate the lowest correlations among the all measurements ($r_p \leq 0.526$).

Conclusions: The Tiger full foot 3D scanner offers both excellent reliability and objectivity in linear measures, which correspond to those obtained by the calliper method. However, values obtained by the both methods shouldn't be used interchangeably. The arch height measure is less accurate, which could limit its use in some clinical applications. Orthotists and related professions probably appreciate scanner more than other specialists.

Foot dimension information is important both for footwear design and clinical applications, for example the classification of the foot type.[1–3] Poorly designed and ill-fitting shoes can result in hallux valgus, hammer toes and other disabling problems,[4,5] while abnormal height of the medial longitudinal arch of the foot is commonly thought to be a predisposing factor to injuries.[6] The available evidence indicates that up to 72% of population is wearing inappropriately sized footwear based on length and width measurements.[5,7]

While there are usually no problems with estimating the foot length and width, according to Razeghi and Batt no general consensus exists on an ideal method for the foot type classification.[2] Yet normalised truncated navicular height (NTNH) was proved to be a reliable, valid and diagnostically accurate clinical measure of static foot posture in children and adolescents[8] as well as the adults.[6] On the other hand, Menz et al. reported only "fair to good" test-retest reliability of navicular height (NH) in elderly.[9] This could potentially affect the reliability of the NTNH. Authors however highlight, that in cases with only little variability

among subjects' scores, it is difficult to obtain a high interclass correlation coefficient (ICC) and therefore conclude, that based on the low coefficient of variation, this measurement could be useful in assessment of older adults' foot posture.[9] Nevertheless, obtaining all mentioned foot dimensions during a single session can be time-consuming, especially when screening of large groups of people is intended.

In recent years, non-contact three-dimensional foot digitizers (e.g. optical laser scanning systems) became popular among researchers as they are non-invasive and are both valid and reliable for the most of length, height and circumference/girth measures.[3,10,11] Also, the indisputable advantage of these devices is the acquisition of several measures at the same time. However, because of the necessity of external marker placement, the measurement could be still relatively lengthy and requires training in palpation and markers placement. Therefore, the possibility of automated calculation of basic foot dimensions is desirable. Although some devices offer such calculations, their reliability, objectivity and validity have not been widely investigated yet.

The Tiger full foot 3D scanner (RSscan International NV, Paal, Belgium) offers automated calculation of the basic foot dimensions without the necessity of external markers placement. Manufacturer declares standard deviation of measurements equal to 0.5 mm and the scanning time approx. 5–15 sec[12]. No specific details about the dimensions' calculations are described by the manufacturer in the product documentation, nevertheless it was found out, that for the

calculation of the medial foot arch height the angle variation on the outside curve of the foot is searched and the maximum height is recognised (Van Rooy T, 12. 12. 2018, writen communication). However, despite the evidence that calliper measures based on the highest point along the soft tissue margin of the medial plantar curvature are both excellently reliable and objective,[13] there are legitimate doubts about the representativeness of the state of bony architecture of the foot by such measures.[6]

Therefore, the study aimed to determine test-retest reliability, objectivity and concurrent validity of the Tiger full foot 3D scanner. In addition, another aim of this study was to assess the relationship between the other two manual measures of the medial longitudinal arch of the foot conventionally used in clinical practice (i.e. NH and NTNH) and its potential alternatives obtained automatically by the scanner.

Materials and Methods

The test-retest reliability was based on an analysis of differences between the three consecutive scanning trials performed by the same rater. Assessing the objectivity (inter-rater reliability), we analysed the differences between the three trials performed by three raters. The concurrent validity of the Tiger full foot 3D scanner was expressed as an agreement between the measured values obtained from the scanner and with a 1-mm scale calliper (Vývojové laboratoře a dílny Univerzity Palackého, Olomouc, Czech Republic).

Participants

Based on the review of Bujang and Baharum,[14] with an alpha-value set at 0.05 and the minimum power of at least 80%, the sample size of 36 participants was required for the test-retest reliability and objectivity assessment with the acceptable and expected reliability values set at $R_0=0.90$ and $R_1=0.95$, respectively. For the confirmation of sufficiency of this sample size both for the objectives of validity and the relationship between the manual and automated methods, the G*Power 3.1.9.2 software (Franz Faul, Universität Kiel, Kiel, Germany) with test "Correlation: Bivariate normal model" was used. With the alpha-value set at 0.05 and the expected population correlation of 0.75, the test power was calculated as 99.9%. Considering additional 15% of possible drop-out rate, altogether 42 young adults (21 males, 21 females) with the mean age 22.4 ± 1.6 years, body height 175.0 ± 9.3 cm and body weight 70.6 ± 12.4 kg, were recruited as subjects. All participants met the inclusion criteria of no pain or discomfort in the plantar or medial aspect of the foot with prolonged standing or walking and the ability of prolonged standing and walking without using any assistive devices.

Further, three research assistants with three years of practice in palpation were approached as the evaluators (rater A, B and C). To satisfy the independence assumption of statistical analysis,[15] measurements of only one (i.e. right) foot were performed.

Study was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and was approved by the Ethical Committee of the Faculty of Physical Culture, Palacký University Olomouc, Czech Republic (reference number 2/2019). All participants signed the informed consent.

Procedures

First, the measurement protocol including predetermined commands (to stand still with the right foot approx. in the middle of scanning surface and the left foot on the step placed next to the scanner; to redistribute the weight equally between the both feet with toes maximally relaxed; to support him-/herself with the right hand on the handrail of the scanner and with the left upper limb along the body; to look forward) was described to the participant in details. Because the different body weight was suggested as a factor influencing foot dimensions,[16] prior to any trial of any procedure, participants were asked to stand simultaneously with each of their feet on one of the two personal weight scales to maximize their ability of equal weight distribution. Following the instructions, subject completed a one scanning procedure for the familiarization with the method and indicative visual inspection of visualisations offered by the Footscan v9 version 9.5.8 software (RSscan International NV, Paal, Belgium) was performed. In case of obviously wrong locations of dimensions, another scan was performed. This process was respected through the whole session.

After the familiarisation procedure, rater A performed three complete foot scans followed by a single scanning procedure performed by rater B, clinical measurements also performed by rater B and another single scanning procedure performed by rater C. The overview of investigated parameters of the scanner as well as their equivalent clinical measures including the abbreviations used in text shows Table 1. As all calliper measures were proven to be reliable,[3,6,8,9,17] only one measurement of each distance was performed.

Because the NTNH definition varies slightly among the individual authors,[6,8,18] in this study the $NTNH_C$ calculation based on the manual (calliper) method was established as a height of the most anterior-inferior portion of the navicular tuberosity from the ground (i.e. the NH_C) divided by the arch length (AL_C) measured from the most posterior portion of calcaneus (the pterion) to the centre of the I. metatarsophalangeal joint. Simultaneously, the normalised truncated arch height based on the data from the scanner ($NTAH_{3D}$) was calculated as the ratio of the arch height (AH_{3D}) and the (AL_{3D}) obtained by the scanner, while the same ratio obtained by the calliper method was not investigated due to its non-using in clinical practice. However, for the purpose of validity, the arch height (AH_C) dimension was manually measured as the highest point along the soft tissue margin of the medial plantar curvature[13] detected visually by the rater B from the ground. The foot width (FW_C) was measured with the calliper as the widest horizontal distance between the I. and V. metatarsal head[3] perpendicular to the imaginary axis of the foot represented by the II. metatarsal. Finally, the foot length (FL_C) was manually

measured as a distance from the pterion to the most anterior point of the longest toe.[3]

Complete dataset was checked for any missing data (e.g. AH_{3D} values in participants with flat foot) and misreports (i.e. obvious non-logical data caused by an error in transcription of measured values).

Statistical analysis

Normal distribution was verified by the Shapiro-Wilk test and the z-test using skewness and kurtosis, following the recommendation of Kim[19]. In accordance to guideline of reliability assessment[20] we determined the ICC using the single measurement/rater, absolute-agreement, 2-way mixed effect model with 95% confidence interval (95% CI) to assess both the reliability (based on three measurements of rater A) and objectivity (based on first measurement of rater A and the measurements of raters B and C) of the scanner. Besides that, the minimal detectable change at 95% CI (MDC_{95}) was also calculated as the indicator of the absolute reliability using the following formulas[21,22]:

$$MDC_{95} = 1.96 \times SEM \times \sqrt{2},$$

where the "SEM" is the standard error of measurement calculated as a square root of the within-subject mean square value taken from the analysis of variance for repeated measures and the "1.96" value is the z-score associated with 95% CI.

Both concurrent validity and relationship between the arch height measures obtained by the two methods were determined by the Pearson's correlation coefficient (r_s) and further by the limits of agreement (LoA) between the scanner and the calliper values using the formula[23]:

$$LoA = d_{mean} \pm 1.96 \times s_d,$$

where the "d_{mean}" is the mean difference, the "s_d" the standard deviation of the differences between the two measurements and the "1.96" value is again the z-score associated with 95% CI. Prior to the calculation of LoA, Spearman's rank correlation was used to reveal potential undesirable significant relationship between the differences and the average scores and necessary logarithmic scores' power transformation was performed in three cases, respecting the approach of Bland and Altman.[23] However, because this failed to remove the relationship, regression approach was applied according to the same authors. The regression equations of the differences between the measurements (D) on the average scores (A) and the absolute values of the regression residuals (R) on "A" were:

$$D = b_0 + b_1 \times A$$

$$R = c_0 + c_1 \times A,$$

where the "b_0" and the "c_0" are the intercepts and the "b_1" and the "c_1" the slopes of the lines respectively. Further, because the regressions of the "R" on the "A" were not significant in all three cases, the standard deviation of the absolute residuals ($SD_{ABSRESID}$) was estimated for the

each of three cases by multiplying its means of the absolute residuals by $\sqrt{(\pi/2)}$.[24] Therefore, obtained regression-based LoA at 95% CI (LoA$_{R95}$) formula was used in form:

$$LoA_{R95} = D \pm 1.96 \times SD_{ABSRESID}.$$

Data management and statistical analysis were undertaken using the SPSS 22.0 (IBM, Armonk, NJ, USA) and the Statistica 13 (TIBCO Software Inc., Palo Alto, CA, USA) software. For all tests, the level of significance was set at $\alpha = 0.05$.

Results

All presented results were statistically significant at the level of 0.05. Both the relative and absolute agreement between the repeated measurements obtained by the Tiger full foot 3D scanner show excellent test-retest reliability and objectivity of linear (FL$_{3D}$, FW$_{3D}$, AL$_{3D}$) measures and only good to nearly good test-retest reliability and objectivity of the arch height (Table 2).

Correlations between the values obtained by the scanner and the calliper were generally higher in linear measures. Also, contrary to the parameters of the foot arch, the scanner overestimates on average both overall foot dimensions, i.e. the FL and the FW (Table 3).

The representativeness of state of bony architecture by the soft tissue margin of the medial foot arch demonstrate the lowest correlations among the all measurements ($r_p \leq 0.526$) with values of the scanner generally underestimated, when compared to the those obtained by the calliper. Therefore, the regression-based equations of LoA have to be used for the conversion of values in forms:

$$-1.2 - 0.9 \times A \pm 5.0,$$

for the relationship between the AH_{3D} and the NH_C parameters and

$$-0.024 - 0.771 \times A \pm 0.027,$$

for the normalised values ($NTAH_{3D}$, $NTNH_C$), where the "A" is the average of values of both methods or the observed value, if only one method is used.

Discussion

Similarly to other studies[3,10,11], linear measures assessed in our study demonstrate excellent (>0.90)[20] test-retest reliability of the Tiger full foot 3D scanner with the SEM values varied between 0.9 and 1.2 mm and the maximal MDC_{95} values equal to 3.3 mm. De Mits et al. repeatedly reported high ICCs (>0.97) and the maximal SEM value of 1.3 mm for the parameters of foot length and width.[10,11] Also, Lee et al. showed ICCs ≥0.95 and the values of mean absolute difference for repeated measurements between 0.79 and 1.50 mm for the same

parameters and the parameter of the "ball of foot length",[3] which corresponds to the AL_{3D} measure of the scanner in this study. Contrary to our research, these studies used external markers, however, modern scanners can easily detect the outermost points,[3] regardless whether it is a marker or a relief of the foot.

Compared to reliability, objectivity of linear measures in our study was slightly lower (yet excellent) with the SEM values varied between 1.1 and 1.7 mm and the maximal value of MDC_{95} equal to 4.8 mm. Since scanning procedure is fully automated, all three raters used the same method and verbal instructions and the AH_{3D} measures show opposite results, the cause could be simply slightly different posture or the error of measurement (especially in the calculation of the AH_{3D}). However, small pauses between each scanning procedure, control of the stance width as well as the presence of personal weight scale under the non-measured foot for the control of weight distribution could be still beneficial in future studies.

We found very high correlation between the scanner and calliper values when assessing concurrent validity. However, the scanner overestimates the calliper method in average in FL and FW by 2.2 mm (± 4.6 mm) and 7.4 mm (± 2.9 mm), respectively. Contrary, the values of AL parameter obtained from the scanner were underestimated in average by 1.2 mm (± 9.9 mm) in comparison to the calliper ones. This can be due to the compression of soft tissues[3] (when the FL_C and the FW_C are measured by the calliper), different area of the FW_{3D} (possibly not strictly restricted to the area of metatarsophalangeal joints) and by the naturally shorter AL_{3D} caused

by the soft tissues contacting the surface more proximal to the heel than in the area of the I. metatarsophalangeal joint, which is the reference point for the standard calliper method adopted in our study. However, specific details about the measurement algorithms of the scanner are not provided by the manufacturer.

Contrary to linear measures, the AH values show slightly worse results, although neither the SEM, nor the MDC_{95} of the AH_{3D} exceed values of linear parameters in both the reliability and objectivity. However, it is important to keep in mind, that absolute values of the AH_{3D} are much smaller than the values of linear measures and the SEM therefore makes up 8% of mean AH_{3D} value for both the reliability and objectivity, while for all the other measures it is less than 2%. This correspond to their relative agreement with only good (0.75–0.90) objectivity and nearly good reliability.[20] However, also Saltzman et al. reported objectivity of only 0.76 when assessed the AH with the calliper,[25] which puts both methods on the same level. Overall lower accuracy of the AH measures could be caused by the different posture or the unconscious contraction of muscles related to medial arch of the foot and maintaining the balance during quiet standing, when the toes remain relaxed as was required. This could possibly affect the AH values much more, than the linear parameters, especially during calliper method, when no handrail was available.

The representativeness of the state of bony architecture by the soft tissue margin of the medial foot arch demonstrates the lowest correlation coefficient among all measurements.

Other authors usually report higher reliability (>0.96) of e.g. NH measures (AH measures are not provided) obtained by the scanner using the external markers.[10,11] However, objectivity of such measures remains unknown with possible lower values due to the issue of palpation as could be suggested by the results of objectivity of NH measures obtained by manual techniques.[6,25] Relationship between the two calculated parameters ($NTAH_{3D}$, $NTAH_C$) is than clearly affected by the low correlation of the corresponding height measures.

Only five spare scans (i.e. 2.4%) had to be done due to the obviously wrong location of at least one measured foot dimension. However, because visualisation lines that represent obtained measures are not mirrored for the right and left foot, it is quite hard to evaluate the visualisation of the right AL_{3D} due to its location on the lateral side of the foot image. Also, in 2 participants with "flatter" feet (NH_C equal to 36 and 37 mm respectively), the scanner was repetitively not able to recognise the arch curve and calculate the AL_{3D} and/or AH_{3D} value. Because (to our knowledge) the 3D scanner doesn't offer the calculations of any foot dimensions with additional markers, using the scanner e.g. for the evaluation of static foot posture isn't possible in individuals with completely missing arch curvature. Therefore, if anthropometric applications are of interest, the calliper method would be probably preferred. Another reason would be probably the cost of the Tiger 3D scanner, which doesn't seem to be redeemed by superior accuracy and/or the number of measured dimensions. On the other hand, if e.g. customisation of foot orthoses using the computer-aided design and manufacturing

(CAD/CAM) approach is intended, the 3D scanner could be beneficial (as presented for example by Telfer et al.[26]), because the arch height calculation doesn't necessary play a role in the process. With regard to this, it should be noted, that the "orthotists, footwear manufacturers and designers" are professions, which the Tiger 3D scanner is originally designed for[12]. This should be kept in mind, when specific clinical applications are of interest.

As suggested, presented study has its limitations. Although maximal attention was paid to the instruction of maintaining the same posture during all trials, neither the stance width nor the weight distribution was controlled exactly, when the measurements were performed. It is also possible, that balance requirements could affect the accuracy of the measurements, especially in the AH parameter obtained by the scanner and during the calliper methods, when no handrail was available. Further, rater B who conducted the manual measurement reported the difficulties in detection of the highest point of medial longitudinal arch of the foot. Possible error in this measurement could be therefore another source of the lower validity of the AH parameter. Finally, because the manufacturer doesn't provide specific details about the measurement algorithms of the scanner, we assume that the definition of measures obtained by the scanner and the calliper measures possibly differ slightly as evident from the values of LoA.

Conclusions

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Our results suggest that the Tiger full foot 3D scanner offers both excellent test-retest reliability and objectivity in linear measures, which correspond to those obtained by the calliper method. However, the definition of measures obtained by the scanner probably differs from those used conventionally in clinical practice. Therefore, values obtained by the both methods shouldn't be used interchangeably. Further, the measure of the arch height is less accurate, which could limit its use in some clinical applications. Orthotists and related professions therefore probably appreciate scanner more than other specialists.

Conflict of Interest: None reported.

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Table 1. Investigated Parameters and Relevant Abbreviations

Parameter	Abbreviation used in 3D scanner	Abbreviation used in calliper methods
Equivalent parameters		
foot length	FL_{3D}	FL_C
horizontal foot width	FW_{3D}	FW_C
arch height	AH_{3D}	AH_C
arch length	AL_{3D}	AL_C
Extra parameters		
navicular height		NH_C
Calculated parameters		
normalised truncated arch height	$NTAH_{3D}$	
normalised truncated navicular height		$NTNH_C$

Table 2. Test-Retest Reliability and Objectivity of Measures Obtained by the Tiger Full Foot 3D Scanner

Parameter	n	ICC	SEM	MDC$_{95}$
Reliability				
FL	42	0.998	0.9	2.6
FW	42	0.982	1.2	3.2
AL	41	0.992	1.2	3.3
AH	40	0.737	1.4	4.0
Objectivity				
FL	42	0.997	1.1	3.1
FW	42	0.959	1.7	4.8
AL	40	0.991	1.3	3.5
AH	40	0.802	1.3	3.5

Abbreviations: n, number of participants used for statistical analysis; ICC, interclass correlation coefficient value; SEM, standard error of measurement (in millimetres); MDC$_{95}$, minimal detectable change at 95% of confidence interval (in millimetres); FL, foot length; FW, horizontal foot width; AL, arch length; AH, arch height

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Table 3. Concurrent Validity of Measures Obtained by the Tiger Full Foot 3D Scanner

Parameter	n	3D scanner[a]	Calliper method[a]	r_p	LoA$_{95}$
FL	42	262.6 ± 18.4	260.4 ± 18.6	0.992	2.2 ± 4.6[b]
FW	40	101.9 ± 8.5	96.5 ± 7.2	0.950	-11.9 + 0.2×A ± 2.9[c]
AL	38	184.2 ± 12.3	185.4 ± 13.4	0.929	-1.2 ± 9.9[b]
AH	37	17.2 ± 2.8	18.8 ± 3.1	0.624	-1.6 ± 5.0[b]

Abbreviations: n, number of participants used for statistical analysis; r_p, Pearson's correlation coefficient; LoA$_{95}$, limits of agreement at 95% of confidence interval; FL, foot length; FW, horizontal foot width; AL, arch length; AH, arch height; A, average of methods or observed value if only one method is used

[a]values are given in millimetres as a mean ± standard deviation

[b]values are given in millimetres as a mean difference between the values obtained by the calliper and 3D scanner ± 1.96 × standard deviation of the differences between values obtained by the 3D scanner and the calliper

[c]regression-based limits of agreement, values are given in millimetres as a difference between the values obtained by the 3D scanner and the calliper ± 1.96 × standard deviation of the absolute residuals