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Comparative analysis of measurement methods for forefoot varus reliability: A systematic review and meta-analysis☆

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ABSTRACT

Background: Forefoot Varus is characterized by inversion of the metatarsal heads relative to the calcaneal bisector. It is present in 83.67 % of cases and contributes to overpronation and related foot/knee/hip pathologies. Despite multiple assessment methods, their reliability remains unclear. This systematic review evaluates the most reliable measurement technique.
Methods: This systematic review and meta-analysis selected studies from several databases: PubMed, Scopus, Cochrane Library, Web of Science, and PEDro. The search strategies included keywords such as “forefoot”, “varus forefoot”, “supinatus forefoot”, “varus alignment of the foot-ankle complex” or “shank-forefoot” and their combinations were used. Studies published in the English, French, and Spanish language were included until July 4th, 2024. After identifying the articles, the methodological quality was assessed using the GRRAS checklist. The reported results were intra-class correlation coefficient, influence on gait, biomechanical factors, and pathologies.
Results: This meta-analysis of 13 studies (n = 1238) found excellent intra-observer reliability for forefoot varus measurements (pooled ICC = 0.92, 95 %CI 0.89–0.94), with significant inter-observer differences (Q = 38.7, p < 0.001): goniometry showed ICCs of 0.56–0.68 (isolated forefoot or JIG shank-forefoot alignment goniometer) versus 0.81–0.91 (shank-forefoot alignment), while photogrammetry maintained consistently higher reliability (ICCs 0.90–0.93). Photogrammetry and goniometry demonstrated moderate correlation between methods (r = 0.71, 95 %CI 0.63–0.78) across predominantly healthy populations studies (76.9 %, mean age 31.5 ± 15.2 years).
Conclusion: Photogrammetric and shank-forefoot alignment methods demonstrate excellent reliability (ICC >0.90) for forefoot varus assessment, while traditional goniometry shows inconsistent results. Standardized protocols are recommended to ensure cross-study comparability.

1. Introduction

Forefoot Varus (FV) is characterized by the inversion of the plane of the metatarsal heads relative to a bisecting line in the sagittal plane of the calcaneus. During human gait the forefoot seeks full contact with the ground, and therefore FV is one of the causes of foot overpronation, which can lead to flat or pronated feet (Donatelli, 1987). Cheung et al. describe overpronation as ‘larger pronation’ during running (Cheung and Ng, 2008), while other studies define it as excessive pronation (Brown and Yavorsky, 1987), hyper-pronation (Kakavas et al., 2023), or

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abnormal pronation (Donatelli, 1987). *This significant variability in terminology, and in the quantitative thresholds used to define these conditions, reflects ongoing debate in the literature.*

Given this correlation between FV and foot overpronation, the forefoot is considered contributing factor in pathologies related to foot overpronation (Hagedorn et al., 2013). Menz et al. identified a statistically significant correlation between foot overpronation and low back pain (Menz et al., 2013). Additionally, this group reported associations between foot pain, pronated foot, and dynamic foot pronation with loss of balance and control of bipedal stance in the elderly population, as observed by Framingham et al. (Menz et al., 2016). Individuals with a FV exhibit greater initial contact forefoot inversion, hindfoot eversion, and ankle inversion moment during walking (Araújo et al., 2020a).

Analyzing the angle of FV reveals that from a young age (14–18 years), during the final stage of foot structure maturation, the inversion angle of the forefoot is related to a higher degree of foot pronation (Silva et al., 2014). Clinical trials have defined the relationship between the severity of FV and increased static and dynamic foot overpronation in adults (Souza et al., 2014). Similarly, it has been shown that flexible flat foot with an average deviation of 5° already generates overpronation under body load (Chen et al., 2003). However, despite this established relation between FV and significant clinical problems, which probably affects the reported incidence of FV in the population ranges between 8, 6 % and 83.67 % (McPoil et al., 1988; Garbalosa et al., 1994). **This wide prevalence range is likely exacerbated by the lack of a consensus measurement method.** Two **primary** methods of evaluating FV exist: 1) assessing the angle between the forefoot and a parallel line (forefoot-hindfoot alignment) (Van Gheluwe et al., 2002; Gross et al., 2007), or 2) assessing the angle between the forefoot and the axis of the leg (commonly known as shank-forefoot alignment) (Mendonça et al., 2013). The trend observed in the most recent publications has stablished the shank-forefoot alignment method as **frequently used, yet no method is universally accepted as the "gold standard"** (Araújo et al., 2020a; Diniz et al., 2020; Machado et al., 2022; Ferreira et al., 2020a). **This lack of a definitive method creates significant clinical uncertainty, hindering both accurate diagnosis and the development of effective, comparable treatment plans. Furthermore, the use of inconsistent methods across studies directly impedes the comparability of research findings, making it difficult to synthesize evidence and establish clear clinical guidelines.**

Furthermore, measurement methods for FV can be divided in goniometric (manual measurement) or photographic (digital measurement). Goniometric methods include the standard goniometer or a jig-goniometer (which has a fixed-arm to improve its reliability) which allows to make a direct manual measurement (Van Gheluwe et al., 2002; Aström and Arvidson, 1995). Photographic methods use a software to standardize the measures taken on a photograph (Gross et al., 2007; Mendonça et al., 2013; Machado et al., 2022; Ferreira et al., 2020a).

To the best of our knowledge, only three studies (Mendonça et al., 2013; Diniz et al., 2020; Aström and Arvidson, 1995) compare measurement methods of FV, and despite these efforts there is not a gold-standard method reported in the literature to measure FV. **This inconsistency in measurement methodology is a critical gap, as it directly undermines the ability to reliably link FV to clinical outcomes and hinders progress in both research and clinical practice. Furthermore, this methodological stagnation limits the field's capacity to integrate emerging technologies, such as 3D motion analysis, wearable sensors and artificial intelligence, which require standardized and reliable input data to reach their full potential.**

With that in mind, the primary objective of this systematic review and meta-analysis is to identify the most reliable measurement system for FV. The intraclass correlation coefficient (ICC) parameter will be used to compare different methodologies. The secondary objectives are to determine the correlation between the FV and other factors of the lower extremity, such as eversion of the hindfoot; and to investigate the correlation between FV and the prevalence or risk factors for injuries. **By establishing a foundation of methodological reliability, this review aims to inform future research and pave the way for the adoption of advanced assessment paradigms.**

2. Methods

This systematic review was designed and conducted in accordance with the guidelines outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al., 2021). This systematic review was registered on the Open Science Framework (OSF) with the Digital Object Identifier (DOI) **10.17605/OSF.IO/BCG5T.**

2.1. Information source and search strategy

Studies were identified by searching the electronic databases, including PubMed, Scopus, Cochrane Library, Web of Science, and PEDro. A comprehensive search strategy was developed using a combination of keywords and Boolean operators. **The final search string used was: (("forefoot varus") OR ("varus forefoot") OR ("forefoot supinatus") OR ("shank-forefoot alignment") OR ("varus alignment" AND foot)) NOT surgery.** Studies published in English, French, and Spanish up to July 4th, 2024, were included. The complete search strategies for all databases are available in Supplementary Material S1.

2.2. Eligibility criteria and study selection

Two independent reviewers (S.C. and M.H.-S.) assessed the studies. Studies were selected based on their title, abstract, and full-text reading, according to the inclusion and exclusion criteria listed in Table 1. In cases of discrepancy, a third independent reviewer (M.D.) was consulted. When abstracts and full texts of potentially eligible articles were not available, the authors of these articles were contacted.

2.3. Identification and selection of sources of evidence

A systematic search was conducted by the two reviewers using the Covidence (Babineau, 2014) and Rayyan (Ouzzani et al., 2016) software for article screening. Duplicates were first eliminated using the Covidence software, and the resulting list was further screened for duplicates using Rayyan (Ouzzani et al., 2016). The two reviewers used Rayyan to apply the inclusion criteria by reading the title and abstract of each article. As there were no discrepancies, the opinion of a third reviewer was not sought. In the final stage, all studies were carefully reviewed, and those that did not describe the source of the ICC data or whose source was referenced from another indexed article were excluded.

2.3.1. Data extraction

The reviewers extracted the data according to an Excel template. The

Table 1
Selection criteria of the studies.

Inclusion Criteria	Exclusion Criteria
- Participants with supinated forefoot alignment (with or without concomitant pathologies) - healthy individuals and pathological populations - Description of forefoot measurement method - Unloaded, static assessment - Report of intra-rater and/or inter-rater reliability metrics (ICC, Kappa, etc.) - Observational studies (cross-sectional, cohort) - Analytical studies	- History of major lower limb surgery - Neurological or systemic conditions affecting foot posture (e.g., cerebral palsy, rheumatoid arthritis) - No quantitative angle measurement reported - Dynamic or loaded-only measurements - ICC or other reliability statistics not reported - Only measurement validity reported without reliability data - Case reports, reviews, conference abstracts - No full-text available

Table 2
Overview studies included in systematic review and meta-analysis.

Authors, year	Design	Gender (M:F)	Age range	Study population	Goal	Type of goal	Measurement Instrument	Observers (ability)	ICC	Subjects	Findings Results	Overall conclusion
Aström, 1995 (Aström and Arvidson, 1995)	Cross sectional	(59:62)	35 (20–50)	Healthy	Discuss concept of “ideal” foot with a set of nonnative goniometric data	VARUS FOREFOOT MEASUREMENT RELIABILITY	jig forefoot and jig shank forefoot goniometric	2 (1R; 1E)	Shank intra 0,91 0,82 inter 0,68. forefoot intra 0,92 0,85 inter 0,56	20	The average was 6° deviation towards the varus of the forefoot	No subjects conformed to the “ideal foot”, which appears to be rare and should be abandoned in favor of clinical observation
Glasoe et al., 2000 (Glasoe et al., 2000)	Cross sectional	(26: 34)	W (valgus 34 ± 13, neutral 34 ± 16, varus 41 ± 21) M (valgus 50 ± 16, neutral 43 ± 20, varus 28 ± 10)	Healthy	Determine the effect of forefoot alignment on dorsal mobility of the first ray Describe any association between forefoot alignment and age on dorsal mobility of the 1st ray	EFFECT OF VARUS FOREFOOT ON OTHER JOINTS	jig forefoot goniometric	1	intra 0,96	20	The forefoot valgus group demonstrated significantly less dorsal mobility of the first ray than neutral or varus groups	Subjects with a varus/ neutral forefoot had > dorsal excursion of the first ray than those with a valgus forefoot
Gheluwe, 2002 (Van Gheluwe et al., 2002)	Cross sectional	(14:16)	24,8 (20–40)	Healthy	Reliability and Accuracy of Biomechanical Measurements of the Lower Extremities	VARUS FOREFOOT MEASUREMENT RELIABILITY	Forefoot goniometric	5 (2R; 3E)	interater 0.61/ 0.62 (L/R) ICC intrarater (0′95-0,99-0,97-0,98-0′99)	30	The interrater ICCs were 0′61/0.62 for left and right, the intrarater ICCs were excellent (>0.95)	Interrater ICCs were quite low, except for measurements of relaxed calcaneal position and forefoot varus. Intrarater ICCs were relatively high for most raters and measurement variables
Gross et al., 2007 (Gross et al., 2007)	Cross sectional	(175:210)	63 ± 8,0	Hip alteration and healthy	Explore cross-sectional relationship between varus foot alignment and hip conditions in older adults	EFFECT OF VARUS FOREFOOT ON OTHER JOINTS	Forefoot photogrammetric	2	intra test retest 0,88, 0,91 (6–12 months), inter 0,93	385	The mean ± SD forefoot varus alignment was 9.9 ± 9.9°. Subjects in the highest category of forefoot varus alignment had 1.8 times the odds of having ipsilateral hip pain (P for trend = 0.06), 1.9 times the odds of having hip pain or tenderness (P for trend <0.01), and 5.1 times the odds of having undergone Total hip replacement (P for trend = 0.04) compared with those in the lowest category	Forefoot varus malalignment may be associated with ipsilateral hip pain or tenderness and THR in older adults
Bittencourt et al., 2012 (Bittencourt et al., 2012)	Cross sectional	(119:54)	16,6 ± 5	Healthy	Investigate predictors of increased frontal plane knee projection angle in athletes	EFFECT OF VARUS FOREFOOT ON OTHER JOINTS	Shank forefoot alignment photogrammetric	1	0,81 SEM 3,9	14	The shank-forefoot alignment together with de abductor isometric torque and passive hip internal rotation range of motion were predict high predictors of increased frontal plane knee projection angle.	The models captured nonlinear interactions between hip abductor isometric torque, passive hip IR ROM, and shank-forefoot alignment.
Mendonça et al., 2013 (Mendonça et al., 2013)	Cross sectional	(125:75)	15,68 ± 3,86	Healthy	A procedure can capture the combined alignment of the foot-ankle complex	VARUS FOREFOOT MEASUREMENT RELIABILITY	shank forefoot alignment and forefoot photogrammetic	2	forefoot intra 0,91/0,90 inter 0,91 Shank-forefoot intra 0,90/0,93 inter 0,90	11	Intraclass correlation coefficients ranging from 0.82 to 0.93 demonstrated excellent intratester and intertester reliability for the proposed measurements of forefoot, rearfoot, and shank-forefoot alignments. The	This study describes a reliable and practical measurement procedure for rearfoot, forefoot, and shank-forefoot alignments that can be applied to clinical and research situations as a screening

(*continued on next page*)

Table 2 (*continued*)

Authors, year	Design	Gender (M:F)	Age range	Study population	Goal	Type of goal	Measurement Instrument	Observers (ability)	ICC	Subjects	Findings Results	Overall conclusion
											intraclass correlation coefficient between the shank-forefoot measures and the sum of the rearfoot and forefoot measures was 0.98	procedure for risk factors for lower-limb injuries in athletes.
Souza, 2013 (Souza et al., 2014)	Cross sectional	(9:14)	24,6 ± 4,01	Healthy	Test whether measure that combines frontal-plane bone alignment, mobility at the foot ankle complex and hip internal rotation mobility predicts hindfoot kinematics in walking and upright stance	EFFECT OF VARUS FOREFOOT ON OTHER JOINTS	Shank forefoot alignment goniometric	1	intra 0,91	10	The measures significantly predicted (p 0.041) mean eversion/inversion position, during walking (r2 ¼ 0.40) and standing (r2 ¼ 0.31), and eversion peak in walking (r2 ¼ 0.27)	Forefootshank angle and hip internal rotation mobility (alone or in combination) partially predicted hindfoot kinematics. These measures may help detecting foot, ankle and hip mechanical variables possibly involved in an observed hindfoot motion or posture.
Mendonça et al., 2018 (Mendonça et al., 2018)	Cross sectional	(145:47)	17,85 ± 4,72	Patellar tendinopathy and healthy	Investigate impairments of the hip and foot/ankle associated with patellar tendinopathy.	EFFECT OF VARUS FOREFOOT ON OTHER JOINTS	Shank forefoot alignment photogrammetric	2 (2E)	intra 0,93 inter 0,90	10	Interactions among passive hip IR ROM, SFA, hip ER and abductor strength identified athletes with and without PT. The model achieved 71.2 % sensitivity and 74.4 % specificity. The area under the ROC curve was 0.77 (95 % confidence interval: 0.70–0.84; (p < 0.0001).	Impairments of the hip and foot/ankle are associated with the presence of PT in volleyball and basketball athletes. Future studies should evaluate the role of these impairments in the etiology of PT.
Cruz et al., 2019 (Cruz et al., 2019)	Randomized clinical trail	(0:53)	21,75		To evaluate the effects of hip/trunk muscle strengthening on pelvic/hip kinematics during walking based on FAC varus alignment	EFFECT OF VARUS FOREFOOT ON OTHER JOINTS	Shank forefoot alignment goniometric	2	intra 0,93	10	The subgroup with smaller varus alignment, of the intervention group, presented a reduction in pelvic drop after strengthening (P = 0 03). The subgroup with larger varus alignment increased pelvic drop after strengthening, with a marginal significance (P = 0 06). The other kinematic excursions did not change (pelvic anterior rotation P = 0 30, hip internal rotation P = 0 54, and hip adduction P = 0 43).	These results suggest that FAC varus alignment influences the effects of strengthening and should be considered when hip and trunk muscle strengthening is used to reduce pelvic drop during walking.
Araujo, 2020 (Araújo et al., 2020b)	Cross sectional	(11:17)	22,04 ± 4,02	Healthy	The effect of varus alignment of the foot-ankle complex on the kinematics and kinetics of foot, ankle, knee, and hip in the frontal and transverse planes during walking	EFFECT OF VARUS FOREFOOT ON OTHER JOINTS	Shank forefoot alignment photogrammetric	2 (2E)	intra 0,91/0,95	10	The group of large varus alignment showed significantly higher (p < 0.03) 31 forefoot inversion angle at initial contact, amplitude of hindfoot-shank eversion, and peak 32 of inversion ankle moment	Large varus alignment of the foot-ankle complex may increase the magnitude of foot pronation and ankle inversion moment during walking
Diniz et al., 2020 (Diniz	Cross sectional	(30:0)	17,59 ± 0,28	Healthy	Investigate the correlation between goniometric and	VARUS FOREFOOT	Shank forefoot alignment	1	0.81 goniometric 0.90	10	A reliability study determined the ICC 3,3 for intra-rater	A reliable and practical measurement procedure

(*continued on next page*)

Table 2 (*continued*)

Authors, year	Design	Gender (M:F)	Age range	Study population	Goal	Type of goal	Measurement Instrument	Observers (ability)	ICC	Subjects	Findings Results	Overall conclusion
et al., 2020)					photogrammetric assessment of shank forefoot alignment in athletes	MEASUREMENT RELIABILITY	photogrammetric and goniometric		photographic. R pearson 0′71.		reliability of 0.90 for photogrammetry and of 0.81 for goniometry assessment. The correlation ($p < 0.001$) between these two measurements was 0.71, which indicates a moderate relationship	for shank-forefoot alignment using the universal goniometer can be easily applied in clinical context
Ferreira 2020 (Ferreira et al., 2020b)	Cross sectional	(41:10)	35,94 ± 8,84	Achilles' tendinopathy and healthy	To investigate the interaction of ankle-foot complex and hip joint factors with Achilles Tendinopathy occurrence in recreational runners	EFFECT OF VARUS FOREFOOT ON OTHER JOINTS	Shank forefoot alignment photogrammetric	3	inter 0,94 intra 0,92	7	The study showed that individuals with higher PF torque, SFA varus, ER torque, but reduced passive hip IR ROM had an 87 % increased likelihood (PR = 1.87) of AT.	Interactions between hip and foot factors could accurately classify recreational runners with and without AT
Machado et al., 2022 (Machado et al., 2022)	Cross sectional	(161:71)	17.8 ± 4.7	Healthy	To identify the influence of lower limb torque, ROM and foot alignment on patellar rotation in healthy athletes.	EFFECT OF VARUS FOREFOOT ON OTHER JOINTS	Shank forefoot alignment photogrammetric	2	inter 0,90 intra 0,93	10	Hip ER isometric torque explained a small part (10 %) of the variance of the Arno angle in healthy athletes (R^2 change = 0.10; unstandardized $\beta = 11.74$ (95 % CI 6.82, 16.65); Standardized Coefficient Beta = 0.32) and sex explained 2 % of its variance (R^2 change = 0.02; unstandardized $\beta = 2.42$ (95 % CI 0.32, 4.52); Standardized Coefficient Beta = 0.15).	SFA was not associated with patellar rotation

extracted data included: study design, evaluation method, measurement properties focusing on reliability, population characteristics, biomechanical correlations, correlations with lower limb pathology, effects on gait, and study limitations.

2.3.2. Quality assessment

In this meta-analysis, the quality and risk of bias of the included studies were assessed based on the Guidelines for Reporting Reliability and Agreement Studies (GRRAS) (Kottner et al., 2011). For the GRRAS tool, the studies were scored on the following aspects: description of the title and abstract, methods, results, discussion and auxiliary material (Supplementary Material S2).

2.4. Statistical analysis

All statistical analysis were conducted using IBM SPSS Statistics 27 and R Studio with a significance level of alpha = 0.05. Thirteen articles published between 1995 and 2022 were analyzed. The following variables were collected for each publication:

- Demographic variables of study participants: age (mean and standard deviation), number of individuals participating, gender and patient status (healthy, well and with pathology),
- Study design variables: objective of the study, type of measurement and number of observers.
- Variables relating to the kappa index:
- ICC_shank-forefoot alignment first and second observer and between observers
- ICC_ forefoot first and second observer and between observers

The intraclass correlation coefficient reported in the studies about the forefoot measurements has been considered. This coefficient measures the overall agreement between two or more quantitative measurements obtained with different measuring instruments or assessors. It is based on a repeated measures analysis of variance model. However, its use is only possible if there is normality of the distributions of the variables, equality of variances and independence between the errors produced by the observers.

Let σ_α^2 the variance of each subject and be σ_{obs}^2 the inter-observer variance of each subject. The ICC is given by the following expression:

$$ICC = \frac{\sigma_\alpha^2}{\sigma_\alpha^2 + \sigma_{obs}^2} \quad [1]$$

This coefficient gives values between 0 and 1, where 0 means no concordance and 1 means concordance or absolute reliability. The following values are conventionally accepted:

- ICC$<$ 0.40: Poor.
- 0,4 $\leq$ ICC $\leq$ 00,59: Sufficient.
- 0.60 $\leq$ ICC $\leq$ 0.74: Good.
- ICC $\geq$ 0.751: Excellent.

Confidence intervals have been constructed according to equations [2] and [3] for each ICC reported by the different studies evaluated to compare the results between different authors and to look for possible factors influencing the construction of the study. Let K be the number of observers and let n be the sample size of the study, the confidence interval at level (1-α) for the ICC is given by:

$$Var = \frac{2(1-ICC)^2[1+(K-1)ICC]^2}{K(K-1)(n-1)} \quad [2]$$

$$IC_{(1-\alpha)}(ICC) = \left[ICC - Z_{\frac{\alpha}{2}}Var(ICC);\ ICC + Z_{\frac{\alpha}{2}}Var(ICC)\right] \quad [3]$$

To analyze possible differences between the different factors (number of observers, technique used, type of subjects under study), associated ANOVA tables were constructed.

The I^2 metric has been used as a measure of heterogeneity as it allows for a more consistent comparison of heterogeneity between different meta-analyses, regardless of the number of studies (Higgins and Thompson, 2002) and τ^2 which is insensitive to the number of studies, and their precision as it does not systematically increase as the number of studies and their size increases (Veroniki et al., 2016; Sidik and Jonkman, 2002; Viechtbauer, 2005). Forest plots among studies have been done by thecnic and measurement instrument.

3. Results

3.1. Search strategy

The included studies were published up to July 4th, 2024. The database search retrieved 1011 articles: 395 from Cochrane Library, 295 from PubMed, 291 from Web of Science, 25 from Scopus, and 5 from PEDro. After duplicate records were removed, a total of 767 studies were screened. Of the 767 article titles and abstracts screened, 74 articles were eligible for full-text assessment. Finally, 13 studies were selected for the quantitative and qualitative assessment (see Table 2). The PRISMA flow diagram is shown in Fig. 1.

3.2. Qualitative review

3.2.1. Meta-analysis

The meta-analysis revealed several key findings regarding the reliability of forefoot varus measurement methods. A large variability was observed in the number of subjects considered in each of the investigations included in this study. The range of variation in the size of the study population was [23,385] individuals categorized as healthy or as healthy and with other pathologies. 76.9 % (10 **out of 13** publications) of the studies considered only healthy patients while 23.1 % (3 studies) considered a mix of healthy patients and those with some pathology. Fig. 2 shows the sample size in each study, and Fig. 3 shows the proportion of males and females in each study.

The age of patients in each study ranged from [18, 77] years. The average age weighed by the population sizes considered in each study was 31.5 years. Fig. 4 shows the box plot of the average age of the participants according to the study considered and the average age of the patients overall. Of note is the study by Gross et al. (2007) which considered a set of patients with a higher average age than the other authors.

The number of observers in each study ranged from [1, 5]. Fig. 5 shows the percentage of the number of observers considered in the studies analyzed. It should be noted that half of the studies included two observers, four studies had only one observer, one study had three observers, and one study had five observers.

The forefoot ICC was collected from all studies, as proposed by Scherjon et al. (Kok et al., 1993) Stratford et al. (1984), in order to measure reproducibility by considering the fraction between subject variation (S_α^2) and the variance obtained by measurement error, derived mainly between different observers (S_{obs}^2). Fig. 6 shows the confidence intervals of each ICC for the cases in which the study considered more than one observer and the value of the ICC when only a single observer was considered. Fig. 7 presents the associated forest plot, τ^2 and I^2 statistic, which indicates substantial heterogeneity among authors. It should be noted that the variability is calculated with respect to the number of observers, and the majority of the studies considered reported only a single observer. Consequently, the resulting variability is minimal.

Of note is the study by Bittencourt et al. (2012) where the reported ICC falls outside the range of the remaining studies, being significantly lower compared to the others. If we consider again the graph of the confidence intervals for each ICC without the influence of this study

(Fig. 8), we can observe that the remaining studies provide significantly high ICC values, highlighting the study provided by Gheluwe et al. (Van Gheluwe et al., 2002) Fig. 9 shows the box plot for the ICC reported by the different authors.

One factor that can lead to low ICC is the excessive increase in the number of observers. The consideration of healthy or non-healthy subjects in the study was not a significant factor (p-value = 0.926; F-Snedecor = 1.312) in the ICC measure reported by the analyzed studies, nor was the type of technique: photographic or goniometric (p-value = 0.721; F-Snedecor = 2.788). Regarding the measuring instrument, no differences were observed according to the type of instrument (p-value = 0.124; F-Snedecor = 2.63). However, a difference in variability is observed according to the type of technique, with lower variability of ICC reported in the case of studies with photographic techniques (SD = 0.059) compared to goniometric techniques (SD = 0.034), although these differences are not significant (Levene's statistic = 2.78, p-value = 0.114) due to the high number of studies that present anomalous data with photographic technique. Fig. 10 shows the box plot with both techniques and Fig. 11 the associated forest plot, τ^2 and I^2 statistic, which indicates substantial heterogeneity among techniques. Fig. 12 shows the box plot according to the type of measuring instrument (shank forefoot alignment or forefoot) and Fig. 13 the associated forest plot, τ^2 and I^2 statistic which indicates substantial heterogeneity among measurement instruments.

For studies with more than one observer, Fig. 14 shows the confidence intervals of each inter-observer ICC, and Fig. 15 shows the box plot.

Of note are the studies by Aström et al. (Aström and Arvidson, 1995) and Gheluwe et al. (Van Gheluwe et al., 2002), where the reported ICC falls outside the range of the remaining studies, being significantly lower compared to the others. If we consider again the graph of the confidence intervals for each ICC without the influence of these studies, we can observe that the remaining studies provide significantly high ICC values.

Again, the consideration of healthy or non-healthy subjects in the study was not a significant factor (p-value = 0.104; F-Snedecor = 3.366) in the ICC measure reported by the analyzed studies, not was the type of technique: photographic or goniometric (p-value<0.001; F-Snedecor = 650.1), with the ICCs reported in studies using goniometric techniques (mean = 0.578) being significantly lower than those using photographic techniques (mean = 0.920). Similarly, no significant differences were observed according to the measuring instrument (p-value = 0.617; F-Snedecor = 0.271). However, a difference in variability is observed according to the type of technique, with greater variability of ICCs reported in studies using forefoot techniques (standard deviation = 0.185) compared to shank techniques (standard deviation = 0.16), although these differences are not significant (Levene's statistic = 0.98, p-value = 0.351). Fig. 16 shows the box plot and Fig. 17 according to the type of measuring instrument. If the study reported by Aström (1995) is removed from the analysis, there are significant differences with respect to variability according to the measuring instrument (p-value = 0.038; Levene's statistic = 7.034), with greater variability of ICCs reported in studies using forefoot techniques (standard deviation = 0.154) compared to shank techniques (standard deviation = 0.15).

4. Discussion

4.1. Summary of evidence and methodological evolution

In this meta-analysis, we observed a modest body of evidence reporting measures of forefoot varus. There was no consistently used measure to determine forefoot varus, and the choice of measurement methods was often arbitrary. Additionally, the validity and reliability of these measures were rarely justified. Within the scope of this review, only forefoot and shank forefoot alignment had published data supporting their validity and reliability.

The methodological evolution of forefoot varus assessment has progressed from simple goniometry to jig-assisted goniometry, photogrammetry, and the more recent shank-forefoot alignment technique. This progression reflects a continuous effort to improve reliability and clinical applicability, moving from static and examiner-dependent measurements towards more standardized approaches. In this systematic review and meta-analysis, forefoot alignment and shank forefoot alignment were used four and nine times, respectively, across this review, with the shank forefoot alignment method being frequently employed. This preference is likely due to the weak to moderate reliability of methods detailed in the literature for assessing forefoot alignment before the introduction of the shank forefoot alignment (SFA) method for intertester reliability (Van Gheluwe et al., 2002; Mendonça et al., 2013; Aström and Arvidson, 1995).

4.2. Clinical implication

Accurately measuring FV during clinical examination is crucial because of its established relationship with foot overpronation and associated lower limb and low back pathologies. A statistically significant association was found between foot overpronation and a higher risk of anterior knee pain in individuals with bilateral flat feet (Ohi et al., 2017) and a positive correlation with patellofemoral pain (Lack et al., 2014). Studies also show a high correlation between tibial periostitis pain and foot overpronation (Neal et al., 2014; Menéndez et al., 2020).

Another study by Kosashvili et al. (2008) indicates that moderate to severe flat feet nearly doubles the incidence of anterior knee pain or intermittent low back pain. Additional research highlights the relationship between foot overpronation and Achilles tendinopathy, either in isolation or combined with other factors (Ferreira et al., 2020b; Mousavi et al., 2019). Finally, Park et al. (2018) described how flat and pronated feet are related to a thicker plantar fascia, a risk factor described for plantar fasciopathy. These findings suggest that an overpronated foot is a risk factor for multiple lower extremity pathologies, and its measurement is essential for the correct assessment and evaluation.

Johanson et al. (2010) described 8 degrees of FV as the value from which foot pronation started to increase. A randomized clinical trial identified three objective differences in static posture between asymptomatic flat foot, neutral/medium asymptomatic flat foot, and symptomatic flat foot. They concluded that greater hindfoot eversion, forefoot abduction, and FV were associated with symptomatic flat foot (Kerr et al., 2015).

Regarding the relationship with neuromuscular control, clinical trials show a reduction in pelvic drop in women with a minor FV and pronated hindfoot, after hip and trunk muscle strengthening. Conversely, there was a tendency for greater pelvic drop in women with a higher FV, suggesting that further studies should measure the clinical ability to modify neuromuscular control according to the magnitude of forefoot deviation (Cruz et al., 2019).

From another perspective, the forefoot varus measure was correlated with some alterations of the lower limb. Glasoe et al. (2000) described that having a varus/neutral aligned forefoot resulted in more dorsal excursion of the first ray than in subjects with a valgus aligned forefoot. Meanwhile, there are some associations with moderate to severe hallux valgus (OR: 10.31) and spring ligament insufficiency (OR: 100.7) with the first ray instability (more dorsal excursion) (Pasapula et al., 2021a). Pasapula et al. studied the relationship between first ray instability and the spring ligament in plantar fasciitis, finding a Pearson's correlation coefficient of 0.82 between these outcomes and illness presence (Pasapula et al., 2021b).

Gross et al. described possible association between forefoot varus and ipsilateral hip pain or tenderness when compare normal values with the highest category of forefoot varus alignment (Gross et al., 2007). One study investigated whether forefoot varus alignment influences the strengthening of trunk and hip muscles. The subgroup with a large deviation of forefoot varus alignment showed increased pelvic drop compared to baseline, while the subgroup with a small deviation reduced pelvic drop with the exercise intervention (Cruz et al., 2019). These results suggest that forefoot varus alignment could be a kinematic risk factor associated with hip pain. Increased pelvic drop can lead to increased hip adduction and compressive load on the gluteal medium/minimus tendons and iliotibial tract, potentially causing changes in the tendon matrix and predisposing these structures to tendinopathy (Grimaldi et al., 2015; Birnbaum et al., 2004; Cook and Purdam, 2012).

Our findings demonstrate that the reviewed methods possess very good intra-rater reliability (>0.8), even for novice examiners (Van Gheluwe et al., 2002; Aström and Arvidson, 1995). This supports their utilization in clinical practice for the longitudinal monitoring of patients. In the context of research, however, the selection of a specific and homogeneously characterized methodology is paramount for achieving cross-study comparability.

4.3. Methodological consideratons and limitations

A key finding of our meta-analysis was the significant impact of methodology on inter-tester reliability.

According to statistical data, we observed a reduction in the variability of inter-observer ICC when excluding Aström et al. (Aström and Arvidson, 1995) study, which did not employ the same angle analysis procedure according to the shank-forefoot alignment method described by Mendonça et al. and subsequently used by the remaining authors in this systematic review (Mendonça et al., 2013). For instance, in numerous studies, the subtalar joint is positioned in a neutral stance during assessment, which has been demonstrated to have inadequate to moderate intertester reliability (Van Gheluwe et al., 2002; Aström and Arvidson, 1995; Picciano et al., 1993; Smith-Oricchio and Harris, 1990; Elveru et al., 1988). Additionally, despite the conventional rationale for measuring subtalar joint alignment in its neutral position, this may not accurately reflect the position assumed by the foot during closed-chain activities (Mendonça et al., 2013).

When analyzing only the SFA method, photogrammetric method (0.90) had greater intraclass correlation values than the goniometric method (0.81) (Diniz et al., 2020). Although Pearson's correlation was moderate (0.71) between these two methods (Akoglu, 2018), it is important to note that there is a 6 degrees of mean difference between methods. This is a significant reason to choose a single method when comparing or measuring over time.

Only two studies of the photogrammetric forefoot alignment had excellent intertester reliability (0.91–0.93). One possible explanation for this could be that the examiner place the ankle in neutral dorsiflexion (0°) using gentle thumb pressure over the third metatarsal head without subtalar joint in neutral stance (Gross et al., 2007; Mendonça et al., 2013), which may result in less measurement error than the neutral talar position.

Some limitation has to be considered derived from the including studies of this review. The low number of studies plus the methodological heterogeneity (patient positioning and examiner training) introduces potential bias. **Variability may arise from insufficient description of bilateral hip–leg alignment and the absence of a standardized framework defining examiner expertise.** Moreover, the inherent nature of forefoot varus as a static, unloaded assessment limits the direct translatability of our findings to dynamic function.

4.4. Future directions and emerging technologies

Future research should address the static nature of current assessment methods by examining the complex relationship between osseous alignment and dynamic function under load. Dynamic three-dimensional biomechanical modelling offers a means to differentiate true bony alignment from soft tissue deformation and compensatory neuromuscular responses, thereby improving the understanding of functional forefoot mechanics (Leardini et al., 2019; Zhu and Jenkyn, 2023). Wearable sensors and smart insoles can provide continuous, real-world data on kinetic and kinematic parameters associated with

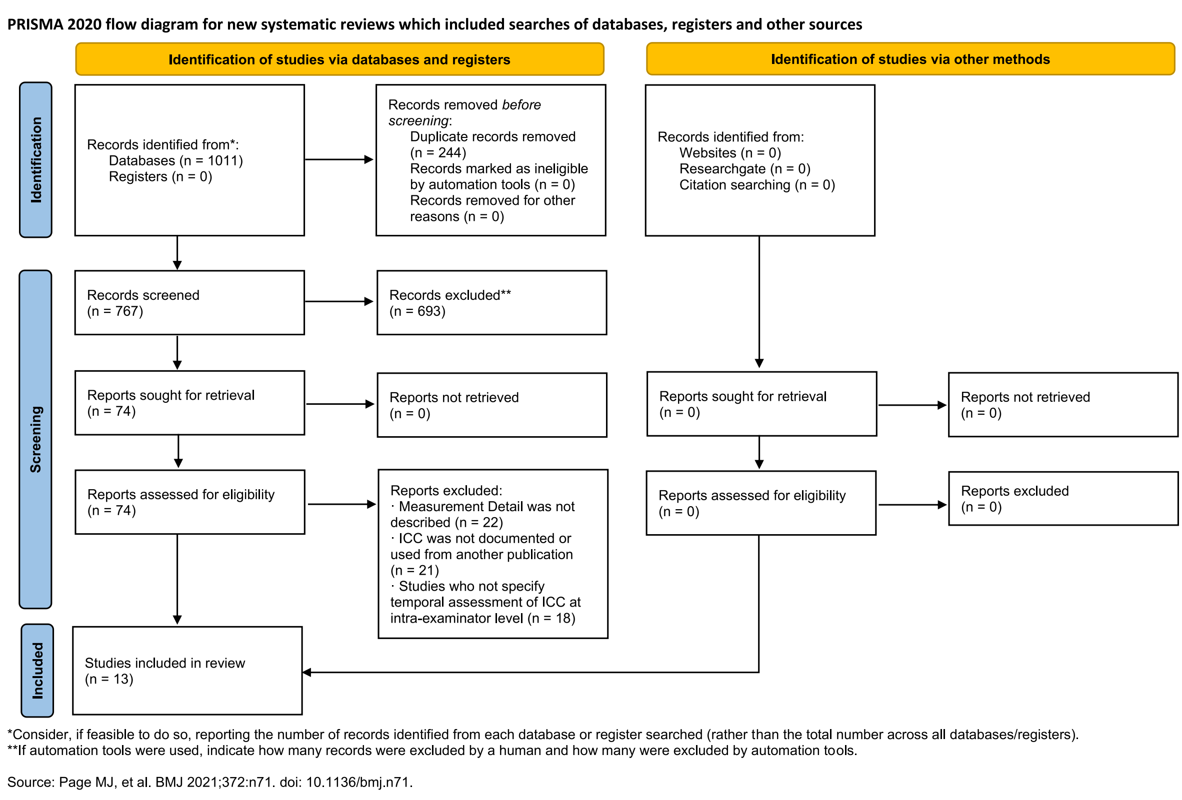

Fig. 1. PRISMA 2020 Flow diagram.

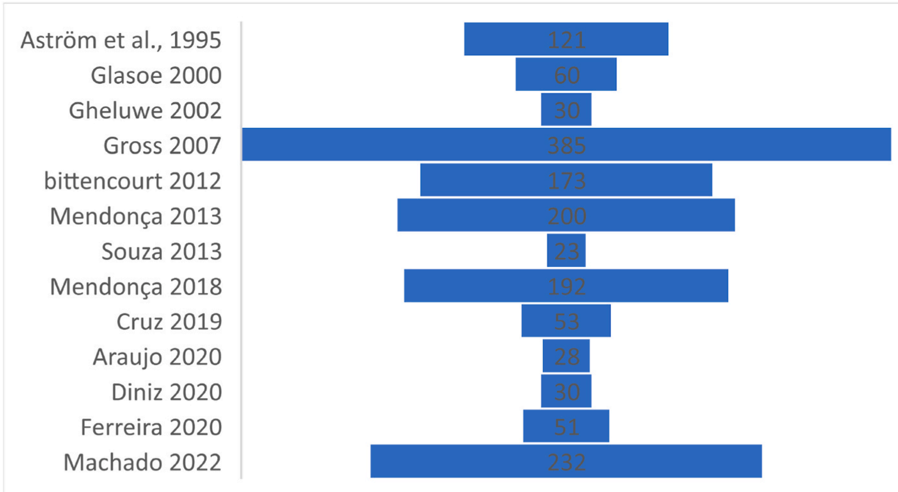

Fig. 2. Funnel plot of sample size for each study considered.

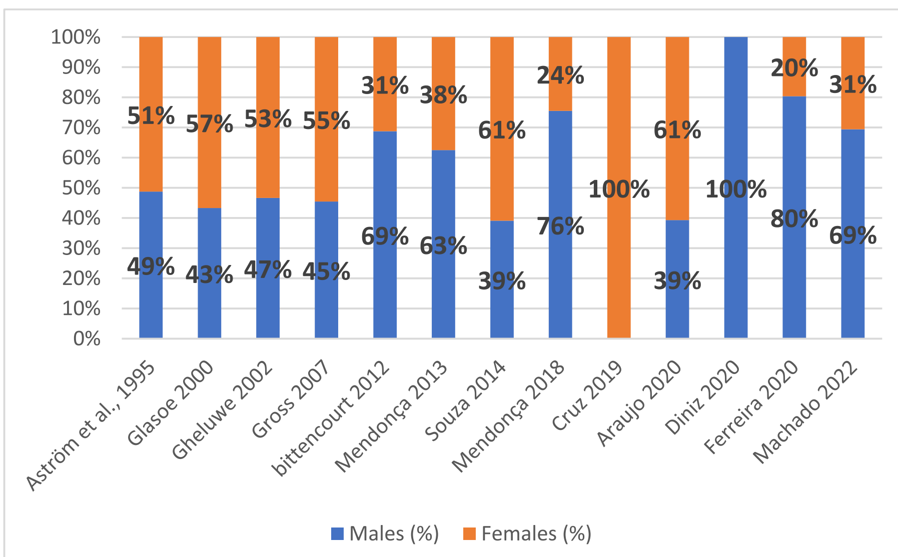

Fig. 3. Proportion of men and women considered in each study.

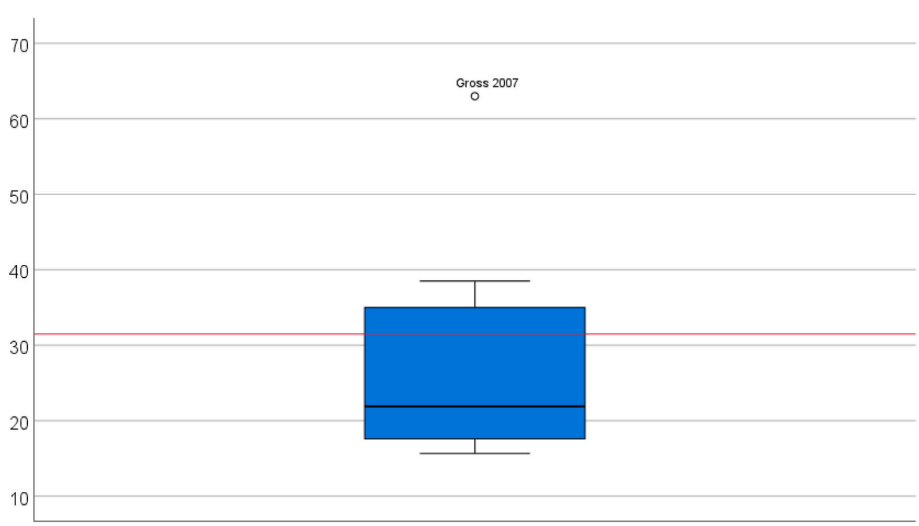

Fig. 4. Box plot of the average age of patients in the set of studies considered. Patient's age.

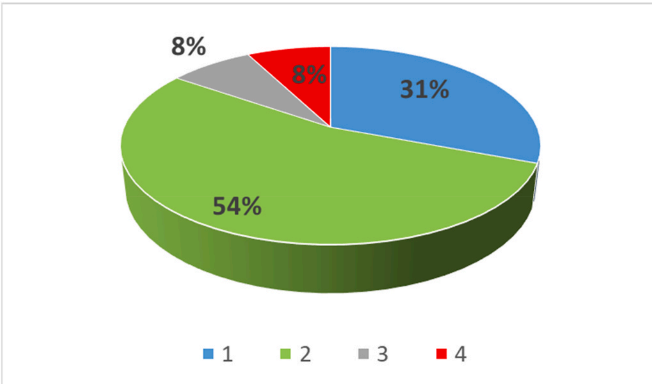

Fig. 5. Percentage of studies analyzed according to the number of observers performing the measurement.

excessive pronation, such as tibial internal rotation, navicular drop, and center of pressure progression (Prisco et al., 2025). Integrating these datasets through artificial intelligence and machine learning will enable the development of predictive models for individualized forefoot assessment and enhance insight into the contribution of forefoot varus to lower-limb function (Zhan et al., 2025; Katmah et al., 2023).

In summation, this analysis clarifies the reliability landscape of forefoot varus assessment while highlighting its clinical significance. The findings advocate for methodological standardization in research while supporting the use of multiple techniques in clinical practice, provided their limitations are recognized. The demonstrated associations with both distal and proximal lower limb pathology underscore the importance of accurate forefoot alignment assessment in comprehensive lower extremity evaluation.

5. Conclusions

Shank-forefoot alignment and photogrammetric methods demonstrated excellent reliability for assessing forefoot varus, making them optimal for both clinical practice and research settings. In contrast, traditional goniometric forefoot alignment showed inconsistent intertester reliability when performed without standardized SFA protocols. To ensure cross-study comparability, we recommend:

1. Adopting photogrammetric SFA or forefoot photogrammetric techniques as the gold standard due to their superior precision.
2. Explicitly reporting measurement protocols (e.g., subtalar joint positioning, examiner training) to minimize variability.

Future research should validate these methods in pathological

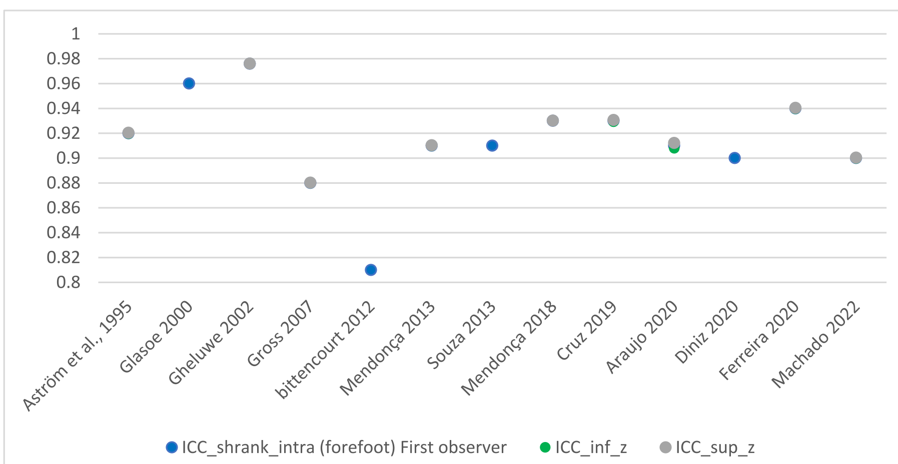

Fig. 6. ICC and confidence intervals for each study analyzed.

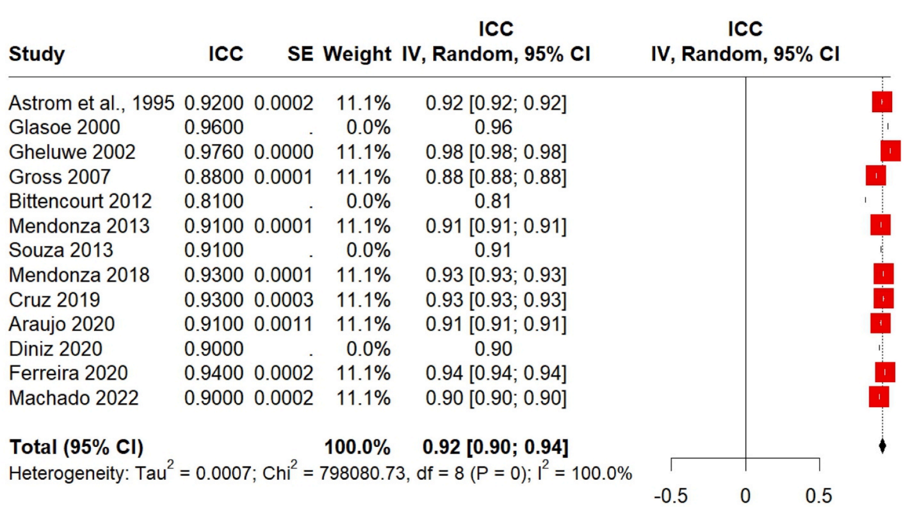

Fig. 7. Forest plot by author and confidence intervals for each study analyzed.

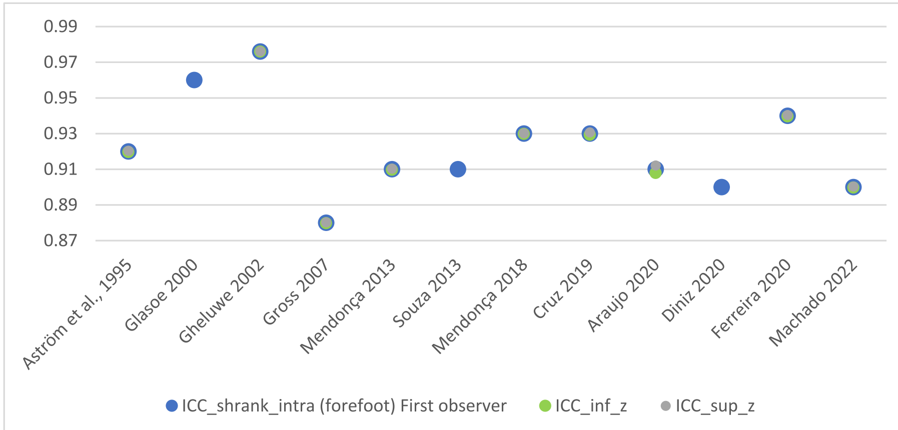

Fig. 8. ICC and confidence intervals for each study analyzed eliminating the study by Bittencourt et al. (2012).

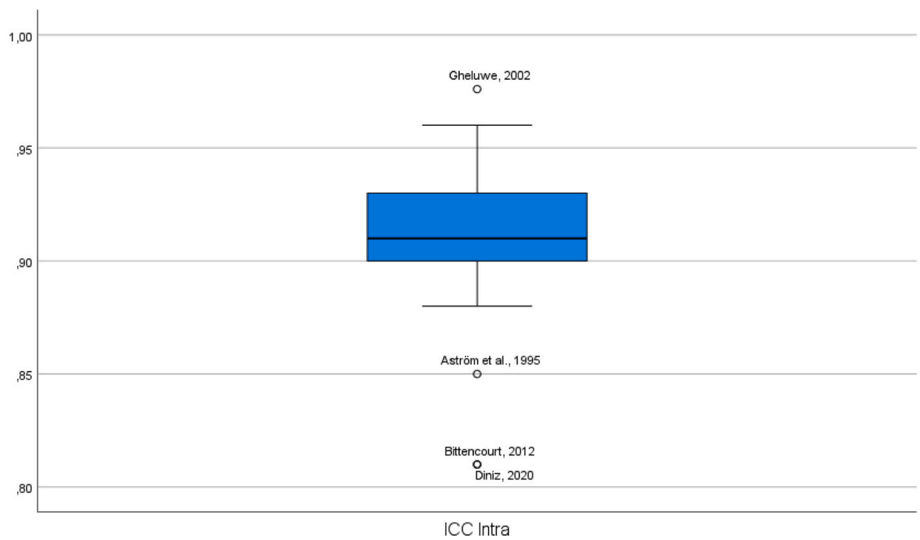

Fig. 9. Box plot for the ICC reported by the author from study previously mentioned.

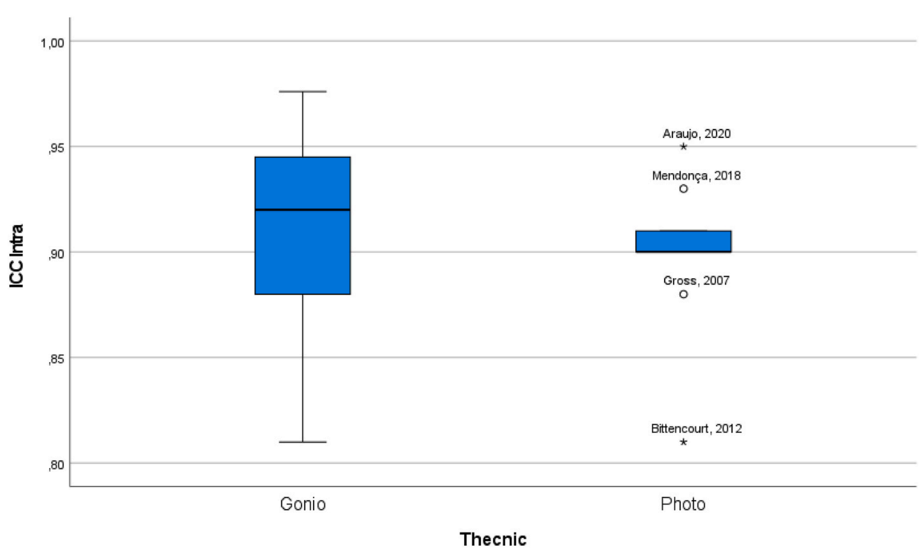

Fig. 10. Intra-observer ICC box plot by technique type.

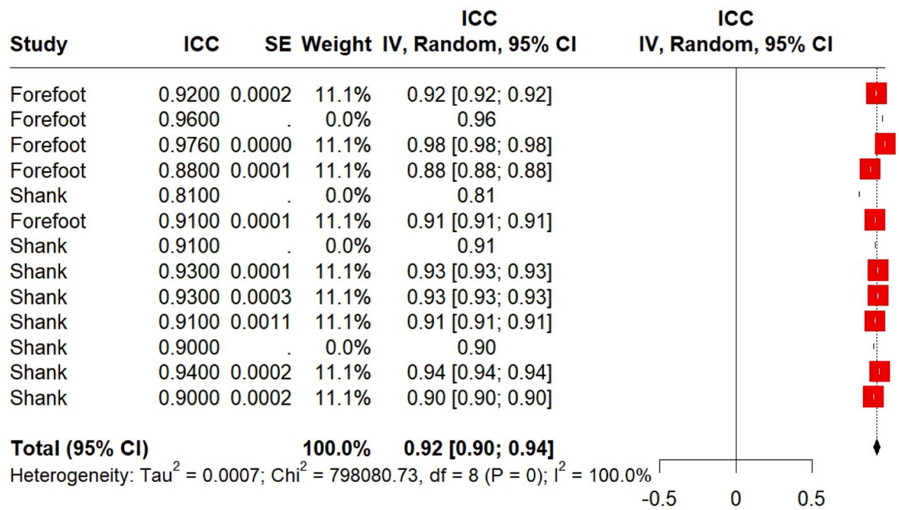

Fig. 11. Intra-observer ICC Forest plot by technique type.

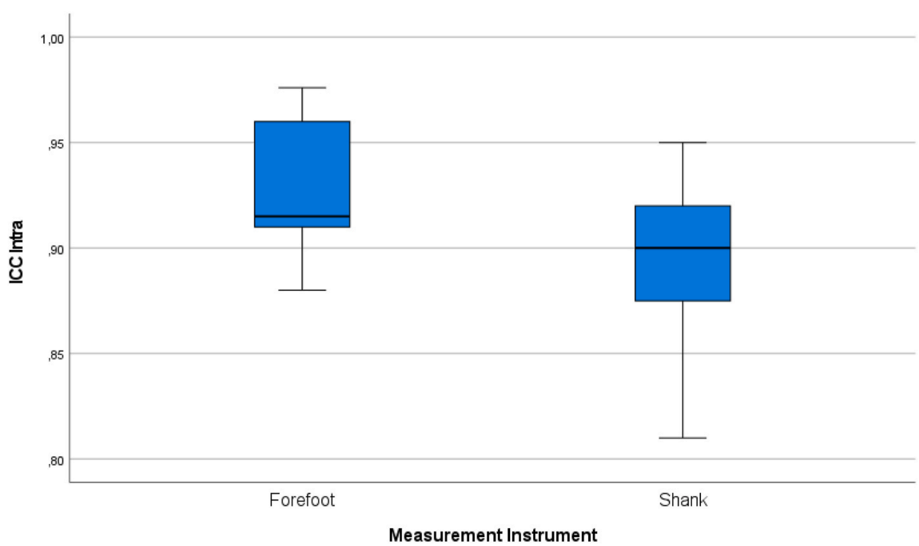

Fig. 12. Intra-observer ICC box plot by measurement instrument.

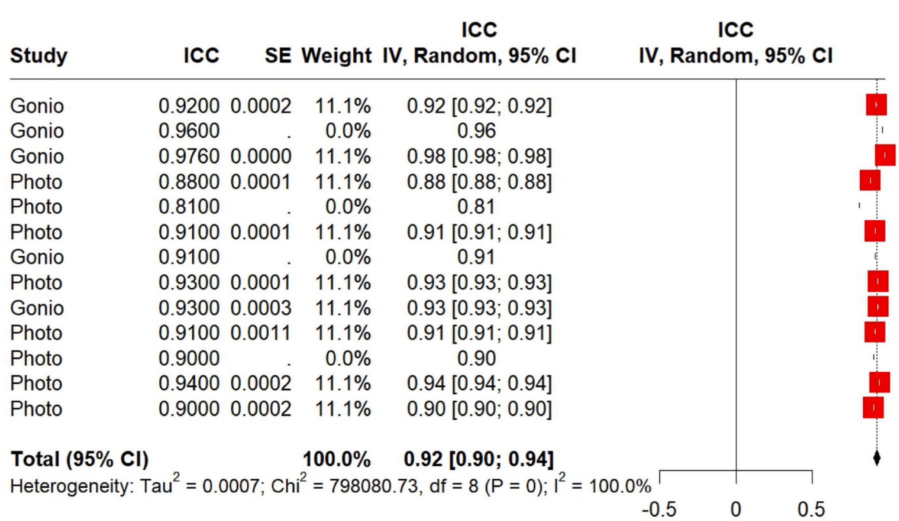

Fig. 13. Intra-observer ICC Forest plot by measurement instrument.

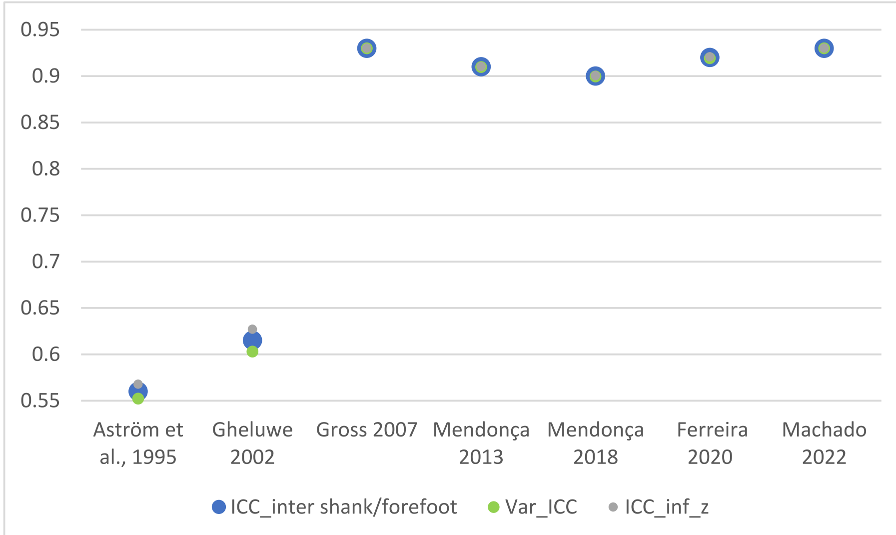

Fig. 14. ICC and confidence intervals for the case where there was more than one observer for each study analyzed.

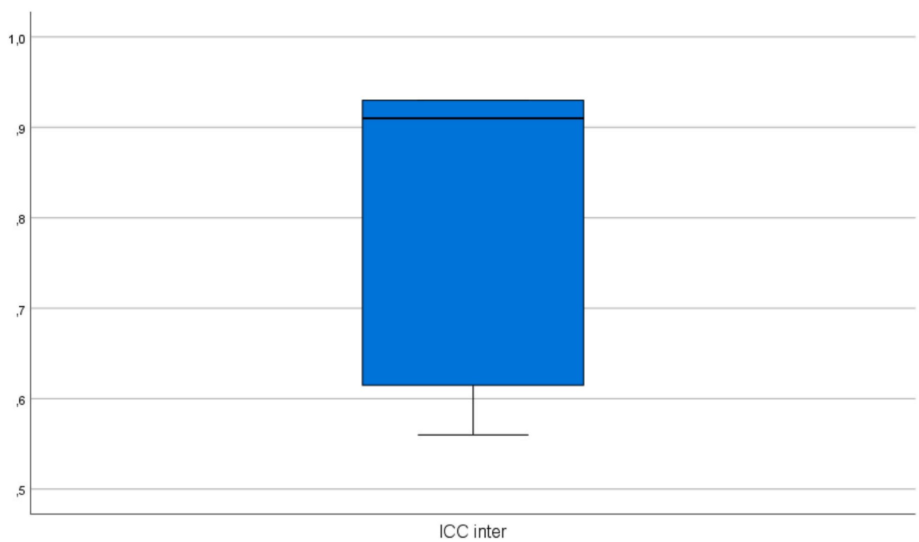

Fig. 15. Inter-observer ICC box plot.

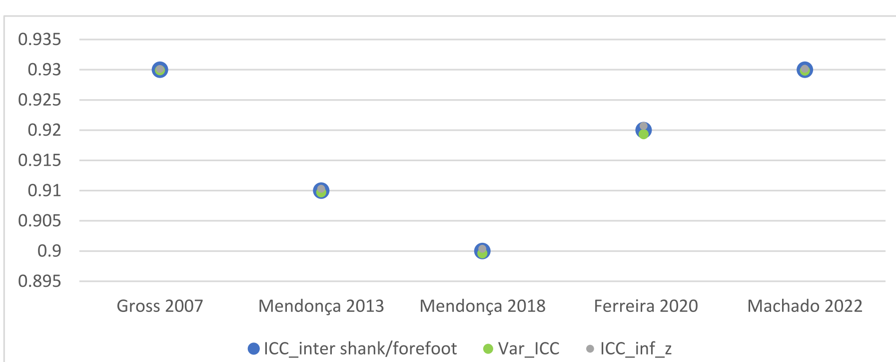

Fig. 16. ICC and confidence intervals for the case where there was more than one observer for each study analyzed eliminating the studies by Aström (1995) and by Gheluwe (2002).

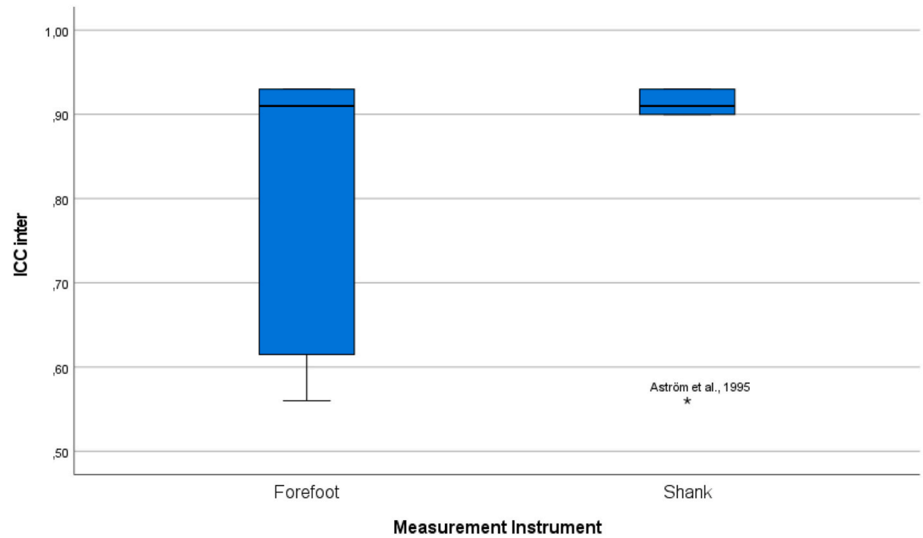

Fig. 17. Inter-observer ICC box plot by measurement instrument.

populations and dynamic conditions to elucidate the role of forefoot varus in lower-limb dysfunction. Integrating wearable sensors and artificial intelligence will be key to defining its biomechanical relevance and confirming it as a modifiable risk factor in lower-limb pathology.

CRediT authorship contribution statement

Sergi Carrelero Camp: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Miki Dalmau-Pastor:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis. **Clara Simón De Blas:** Software, Formal analysis, Data curation. **Carles Vergés Sala:** Writing – review & editing, Methodology, Conceptualization. **Elena De Planell Mas:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Mar Hernández-Secorún:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Project administration, Methodology, Investigation, Conceptualization.

Patient consent

This is a systematic review of previously published studies and does not involve direct contact with human subjects. Therefore, obtaining new ethical approval or patient consent was not required. However, as part of our inclusion criteria, we confirmed that all primary studies included in this synthesis reported obtaining informed consent from participants and/or approval from an institutional ethics review board.

Availability of data

Datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used “Deepseek” in order to use generative AI to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbmt.2025.12.001.

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