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Validity and reliability of hallux valgus angle measured on digital photographs

Sheree Nix, BHSc(Pod)(Hons) [1,2]
Trevor Russell, PhD[3]
Bill Vicenzino, PhD[4]
Michelle Smith, PhD[5]

[1] PhD candidate, The University of Queensland, School of Health and Rehabilitation Sciences, Division of Physiotherapy, Brisbane, Australia.
[2] Lecturer, Queensland University of Technology, School of Clinical Sciences, Brisbane, Australia.
[3] Senior Lecturer, The University of Queensland, School of Health and Rehabilitation Sciences, Division of Physiotherapy, Brisbane, Australia.
[4] Professor and Head of Division of Physiotherapy, The University of Queensland, School of Health and Rehabilitation Sciences, Brisbane, Australia.
[5] Lecturer, The University of Queensland, School of Health and Rehabilitation Sciences, Division of Physiotherapy, Brisbane, Australia.

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Address correspondence to: Dr Michelle Smith, School of Health and Rehabilitation Sciences, The University of Queensland, St Lucia, QLD, 4072, Australia. E-mail: m.smith5@uq.edu.au

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Study Design: Controlled laboratory study.

Objectives: To investigate the reliability and concurrent validity of photographic measurements of hallux valgus angle compared to radiographs as the criterion standard.

Background: Clinical assessment of hallux valgus involves measuring alignment between the first toe and metatarsal on weight-bearing radiographs or grading the severity of deformity visually using categorical scales. Digital photographs offer a non-invasive method of measuring deformity on an exact scale; however, the validity of this technique has not previously been established.

Methods: Thirty-eight subjects (30 female, 8 male) were examined (76 feet; 54 with hallux valgus). Computer software was used to measure hallux valgus angle from digital records of bilateral weight-bearing dorsoplantar foot radiographs and photographs. One examiner measured 76 feet on 2 occasions 2 weeks apart, and a second examiner measured 40 feet on a single occasion. Reliability was investigated by intraclass correlation coefficients (ICCs) and validity by 95% limits of agreement (LA). Pearson's correlation coefficient was also calculated.

Results: Intrarater and interrater reliability were very high (ICCs > 0.96) and 95% LA between photographic and radiographic measurements were acceptable. Measurements from photographs and radiographs were also highly correlated (Pearson's r = 0.96).

Conclusions: Digital photographic measurements of hallux valgus angle are reliable and have acceptable validity compared to weight-bearing radiographs. This method provides a convenient and precise tool in assessment of hallux valgus, while avoiding the cost and radiation exposure associated with x-rays.

Key Words: *measurement; foot deformity; radiograph*

Hallux valgus (HV) is a common foot deformity that presents with lateral deviation of the first toe (hallux) and progressive subluxation of the first metatarsophalangeal joint.[5] It affects approximately 23% of adults[20] and is significantly associated with foot pain, impaired gait, and increased risk of falls in elderly populations.[4, 12, 16, 22, 35] Surgical intervention is often recommended, making HV the most common indication for orthopaedic forefoot surgery.[19] Increasing hallux deviation and joint subluxation have been shown to impact on health-related quality of life,[18] necessitating classification and monitoring of its severity and progression. The commonly advocated measure for this purpose is the HV angle or the hallux and first metatarsal alignment.[8]

Radiographic measures of HV angle are the current criterion standard, being commonly used in clinical practice[31] with an acceptable level of interrater reliability,[26, 28] but they are not always cost-effective or desirable due to exposure to ionizing radiation, especially for repeated measurements. One alternative is to take clinical measurements using a finger goniometer,[8] and while this method has been previously cited as reliable,[1, 11] its criterion validity has not been established. Another alternative is the use of categorical grading scales with 4 or 5 categories of deformity. The Manchester Scale, which is based on visual comparison with 4 standardized photographs of increasing HV severity, has been validated against radiographs and shown to be reliable.[9, 17] Roddy et al[23] validated a similar 5-grade scale based on line drawings for self-reporting of HV. While these scales are useful for classifying severity of deformity, they have limited clinical utility when an incremental measure of the progression of HV deformity is required.

A precise, reliable and valid measurement of HV angle for classifying severity, which eliminates the costs and risks associated with radiographs, would be of great benefit to researchers and clinicians to classify the severity of HV and inform evidence based practice. Validated assessment tools are vital for researchers when evaluating management strategies and conducting epidemiological research.[23] Furthermore, the ability for clinicians to precisely identify individuals with moderate to severe HV (defined by a HV angle equal to or greater than 20 degrees)[5] and monitor progression over a period of time would help inform management decisions.[8] With recent advances in digital imaging technology, photographic measurement methods are being used increasingly in both clinical practice and research;[13, 25] however, the validity of using digital photographs to measure HV angle has not been established. A strong correlation between photographic and radiographic measurements of HV angle has been reported,[33] but reliability data and sufficient detail regarding methodology to allow reproduction of the technique was not provided. Investigation of whether digital photographic measurements can accurately reflect radiographically determined bony alignment is warranted.

The purpose of this study was to investigate the validity of HV angle measurements from photographs taken under standardized conditions, compared to radiographs as the criterion standard. Intrarater and interrater reliability of both methods was also established.

METHODS

Participants

A sample of 38 healthy adults (8 men and 30 women) was recruited to participate in the study through community advertisements seeking volunteers with and without HV. The mean ± standard deviation (SD) age of the participants was 51.8 ± 16.3 years, ranging from 20 to 75 years, and the mean body mass index was 25.8 ± 4.4 kg/m^2, ranging from 18.0 to 36.8 kg/m^2. Potential participants (n = 61) were screened and excluded if they had any previous foot or ankle fractures or surgery (n = 13) or inflammatory arthritis (n = 5). Due to risks associated with exposure to ionizing radiation, potential participants were also excluded if they were pregnant or breastfeeding (n = 5). This study was approved by the Medical Research Ethics Committee at The University of Queensland, Australia. All participants gave written informed consent and the rights of all participants were protected.

Digital Images

To control for potential error introduced by subject positioning and camera placement, the following procedure was used for obtaining digital images. Participants stood in their natural angle and base of gait, as determined by the principal examiner's observation of each participant walking along a 10 meter walkway. The importance of weight-bearing views has been described elsewhere.[34]

A single bilateral weight-bearing dorsoplantar radiograph was obtained for each participant by the same radiographer. A standardized x-ray tube distance (100 cm) and angle (15 degrees from vertical) was used with the x-ray beam centered between left and right feet at the level of the midfoot (FIGURE 1). Two digital photographs were taken by the principal examiner to be measured for intrarater reliability, and the radiographer immediately captured a third photograph to be measured for interrater reliability. Thus, photographic measurements were taken from 3 independent sets of images. The digital camera was held in a standardized position, which was flat against the x-ray tube to reproduce the angle and position of the radiographic image relative to both feet (FIGURE 1). The digital camera used was a Nikon D90 with 18-200mm zoom lens. Images were taken using a focal length of 30mm and aperture set to F4. The highest resolution (12.3 megapixels) was used, with a relatively low ISO (200), to avoid pixilation and ensure clarity for the purpose of locating measurement landmarks.

Measurement Procedure

Measurements were obtained from digital photographs and radiographs using software that has been adapted from a measurement suite (Version 2.3) which ships with the eHAB® telerehabilitation system (NeoRehab, Brisbane). This software has demonstrated high reliability and validity.[24, 25] All digital images were de-identified prior to measurement and saved in a JPEG format compatible with the software (1445 by 960 pixels; 8-bit RGB JPEG). Radiographs were originally obtained in digital format, so conversion was not required and there was no need to measure radiographs by hand.

To determine HV angle from the digital photographs, 4 points were selected by the examiner: 2 visual bisection points for the head and base of the first proximal phalanx, and 2 visual bisection points for the head and base of the first metatarsal bone (FIGURE 2A). The software used these 4 points to calculate the HV angle, which is the angle formed by the intersection of the axes of the first metatarsal and proximal phalanx.

Several methods have been described for bisecting the first metatarsal shaft on radiographs.[28] The method used in this study was in accordance with recommendations from the American Orthopaedic Foot and Ankle Society.[6] Points marking the width of the metaphyseal/diaphyseal region of the proximal phalanx (0.5 to 1cm proximal and distal to the articular surface) and first metatarsal (1 to 2cm proximal and distal to the articular surface) were selected and the software calculated the bisection points and HV angle (FIGURE 2B).

The principal examiner determined reference points and took measurements from the full set of photographs and radiographs (76 feet) on 2 separate occasions 2 weeks apart. That is, on each measurement occasion, each image was independently marked up and an independent measurement produced. To minimize test-retest bias and ensure the examiner was unable to recall previous observations, no reference was made to the data or images in the interim. All photographic measurements were made first in a single measurement session, followed by all radiographic measurements, such that no direct comparison could be made between the radiographs and photographs of individual subjects. A second examiner measured a subset of radiographs and photographs (40 feet), following the measurement protocol described above on a single occasion. Both the principal examiner and second examiner were podiatrists with 3 to 4 years of clinical experience.

At each session, 1 measurement for each foot was recorded from the bilateral radiographs and photographs and used in our analysis. Repeated measurements by the principal examiner (76 feet) were used to calculate intrarater reliability for both photographic and radiographic measurements. The first measurement by the principal examiner and the measurements by the second examiner (40 feet) were used to calculate interrater reliability.

Statistical Methods

Statistical analyses were performed using data from both left and right feet, with each foot considered a separate unit in analysis (n=76). Although this approach is sometimes problematic in clinical research,[14] it can be considered appropriate for studies of this nature, where the aim is to simply compare 2 sets of measurements and not to draw conclusions regarding individual patients.[17] Intrarater and interrater reliability were examined using intraclass correlation coefficients ($ICC_{3,1}$ and $ICC_{2,1}$).[30] These reliability coefficients were then used to generate the standard error of measurement (SEM) as a measure of absolute reliability, using the formula: $SEM = SD \times \sqrt{(1 - ICC)}$.[7] Minimal detectable change (MDC) at the 90% confidence interval (CI) was calculated using the following formula: $MDC = 1.65 \times SEM \times \sqrt{2}$.[10] Furthermore, to facilitate comparison with our validity analysis, the repeatability coefficient (RC) described by Bland and Altman[2] was calculated as follows: the standard deviation of the differences between test and re-test was multiplied by the z-score for 95% confidence limits (1.96).

Validity of photographic measurements compared to radiographs as the criterion standard was assessed by calculating the 95% limits of agreements (LA), which determines the range within which 95% of differences between the 2 measurement methods should lie.[3] Independent t-tests were used to examine differences between the means of photographic and radiographic measurements obtained by the principal examiner, and mean differences (MD) were calculated with their 95% confidence intervals (CI). Mean absolute differences (MAD) and Pearson's correlation coefficient were calculated to further examine the association between photographic and radiographic measurements.

To investigate potential factors contributing to the discrepancy between photographic and radiographic measurements, 95% LA were calculated separately for subgroups according to age (equal to or less than 50 years, greater than 50 years) and HV angle, using all data obtained by the principal examiner. HV severity was defined using the following classification[5]: no deformity (HV angle less than 15 degrees), mild (equal to or greater than 15 degrees and less than 20 degrees), moderate (20 to 40 degrees), or severe (greater than 40 degrees). For the purpose of our subgroup analysis, these categories were collapsed into 2 groups and defined as follows: none or mild deformity (HV angle less than 20 degrees) or moderate to severe deformity (HV angle equal to or greater than 20 degrees). In addition to 95% LA, independent t-tests and calculated mean differences (95% CI) were used to investigate subgroups by age and HV angle.

Interpretation of correlation coefficients was based on the following guidelines: high correlation was represented by coefficients between 0.7 and 0.89, while coefficients of 0.9 or greater indicated very high correlation.[7] An acceptable range for 95% LA between photographic and radiographic measurements was determined a-priori to be ± 6.5 degrees, which is the reported interrater RC for radiographic measurement of HV angle.[27] Statistical analyses were conducted using Stata version 10.[32]

RESULTS

In the overall sample of 76 feet, mean ± SD HV angle was 22.2 ± 10.6 degrees as measured on radiographs. Of the 76 feet studied, 22 were classified as having no HV deformity (HV angle less than 15 degrees), 14 as having a mild deformity (equal to or greater than 15 degrees and less than 20 degrees), 37 as moderate (20 to 40 degrees), and 3 as severe (greater than 40 degrees).

Intrarater Reliability

The $ICC_{3,1}$ for measurements taken by the first examiner on 2 separate occasions (76 feet) was 0.99 for radiographic measurements [95% CI: 0.99 to 1.0] and 0.97 for photographic measurements [95% CI: 0.95 to 0.98], which indicates very high intrarater reliability (TABLE 1). Values for SEM and MDC also indicate high test-retest reliability for radiographic (SEM: 1.1, MDC: 2.5) and photographic measurements (SEM: 1.8, MDC: 4.1).

Interrater Reliability

Comparison of measurements taken by 2 different examiners on 40 feet showed very high interrater reliability for radiographs [$ICC_{2,1}$ 0.99 (CI: 0.98 to 1.0)] and photographs [$ICC_{2,1}$ 0.96 (CI: 0.93 to 0.98)] (TABLE 2). Interrater agreement for photographic measurements was confirmed by relatively small SEM (2.0) and MDC (4.7) values, also shown in TABLE 2.

Validity

Analysis of validity showed acceptable 95% LA (-6.5 to 4.4 degrees) between radiographic and photographic measurements by the first examiner (76 feet), and LA were slightly narrower (-4.9 to 3.5 degrees) for the second examiner who measured 40 feet. Very high correlations between 0.96 and 0.98 were found using Pearson’s correlation coefficient (TABLE 3). Further analysis of the first examiner's data by age and HV angle subgroups showed narrower 95% LA for measurements made on participants aged 50 years or younger (LA -5.8 to 3.6 degrees) and those with a HV angle less than 20 degrees (LA -6.2 to 3.2 degrees) (TABLE 4).

DISCUSSION

This study compared digital photographic measurements of HV angle with hallux alignment on weight-bearing dorsoplantar radiographs, showing an acceptable level of agreement. Statistical analysis using 95% LA is used to detect possible discrepancy between 2 measurement methods, by indicating the range between which 95% of differences should lie. We determined from the literature that up to ± 6.5 degrees of variation can be seen when more than 1 examiner measures radiographic HV angle.[27] Therefore, this amount of error was considered an appropriate clinical standard for our analysis. Our results showed LA within this range, indicating that photographic measurements of HV angle can be confidently used as an alternative to radiographs.

To interpret results for validity, the repeatability of both photographic and radiographic measurements needed to be established separately. Intrarater and interrater reliability was demonstrated by very high ICCs (> 0.96). These findings are consistent with reports from previous studies investigating repeatability of radiographic HV angle measurements (ICCs > 0.95).[26, 29] Calculated SEM for photographic measurements indicates a likely variation of approximately 2 degrees in either direction due to measurement error. However, MDC at the 90% confidence level was less than 5 degrees (intrarater: 4.1 degrees; interrater: 4.7 degrees), demonstrating good repeatability. Furthermore, we calculated the RC,[2] which can be directly compared to the 95% LA. As can be seen by comparing TABLES 1-3, the RC for photographic measurements were of a similar magnitude to the 95% LA between photographic and radiographic measurements. This indicates that the extent of potential discrepancy between the 2 measurement methods is primarily determined by the level of repeatability of photographic measurements of HV angle.

Because weight-bearing dorsoplantar radiographs are the current standard in clinical practice, they were considered to be an appropriate criterion standard for assessing concurrent validity.[31] Clinical measurement of HV angle has been recommended when it is not possible or necessary to obtain radiographs, as this measure is useful for classifying severity of deformity and monitoring progression over time.[8, 17] Clinical assessment should also include attention to the patient's presenting complaint, which may involve foot pain or cosmetic concerns particularly severity of HV angle.[8] In individuals who do not have pain, Ferrari[8] recommends a waiting period to determine if the condition is deteriorating prior to introducing any treatment aimed at prevention, because there is no evidence to suggest that conservative interventions are more effective in mild HV. Therefore, baseline and follow-up measures of both HV angle and foot pain should inform management decisions. Our study investigated HV angle as a primary indicator of HV severity; however, it should be noted that a thorough pre-operative assessment of HV includes measurement of other radiographic angles such as intermetatarsal angle and distal metatarsal articular angle,[31] in addition to noting the presence of sesamoid displacement and degenerative change.[21] Therefore, radiographs would still be required in individuals with HV for whom surgical correction is being considered.

Several limitations should be considered when applying these results clinically. Possible sources of error when using this method include subject positioning, camera placement, and locating landmarks on the images. We used each subject’s angle and base of gait as a standardized position, which can be easily reproduced in a clinical setting. The camera position was determined by the standard tube to film distance and angle of the radiography equipment. By controlling for potential bias introduced by subject positioning and camera placement, we were primarily investigating the reliability and validity of locating measurement landmarks for HV angle on digital photographs and radiographs independently. Therefore, this method has been validated for use under ideal conditions in a laboratory setting, and further work is required to validate a standardized camera position that would be appropriate for use in a clinical setting.

Another limitation of this method is that visually determining the position of the first metatarsal shaft using a photograph requires a good knowledge of surface anatomy of the foot. Both examiners who took measurements in this study were podiatrists, and while they may be considered representative of any healthcare professional with a good knowledge of anatomy of the foot, perhaps examiners with less experience in treating the foot may exhibit less repeatable results. It has been suggested that systematic differences between radiographic and photographic measurements may occur due to the effect of soft tissue in photographs.[13] However, in our validity analysis (TABLE 3) we found the mean radiographic HV angle (21.6 ± 10.1) and mean photographic HV angle (22.7 ± 9.9) to differ by approximately 1 degree; therefore, any difference does not appear to be systematic. Independent t-test results also showed that this difference was not significant ($p = 0.37$).

The sample of volunteers recruited was representative of a clinical population, with a wide range of ages and severity of HV. The range of HV angles observed in our sample of 76 feet was 3 to 46 degrees, with a range of mild, moderate, and severe HV, as well as 22 feet with no deformity (8 participants with no HV deformity and 6 individuals with unilateral HV). It is interesting to note that further analysis of our validity data by subgroups of HV severity indicated slightly narrower 95% LA when examining feet with mild or no HV deformity (< 20 degrees) (TABLE 4). It is possible that greater measurement error may occur when examining feet with moderate to severe HV (HV angle ≥ 20 degrees), as joint subluxation or development of a medial bursa may lead to inaccuracy in determining the first metatarsal head reference point on a digital photograph.

In comparison to previously validated categorical rating scales, digital photographs provide clinicians with a measurement scale with finer intervals. The 4-level Manchester Scale has been shown to have good retest reliability (weighted kappa = 0.78 to 0.90)[15] and a strong association with radiographic HV angle measurements (Spearman's rho = 0.73, p < 0.01).[17] Similarly, a 5-grade scale described by Roddy et al[23] has been shown to have very good observer repeatability (weighted kappa = 0.82). While this measurement tool has 1 more level of grading than the Manchester Scale, it was designed for the collection of self-report data and uses simplified line drawings that may be less accurate in reflecting the underlying bone alignment. One of the clear benefits of photographic measurements over these categorical scales is that they produce a finer incremental measurement, which is important due to the progressive nature of HV. Furthermore, while goniometric measurements have been reported to have good test-retest reliability (r =

0.71),[1] their validity compared to radiographic measurements has not been established, and this should be investigated in future clinical studies.

A clear benefit of photographic measurements is the non-invasive nature of this technique and its cost-effectiveness for researchers and clinicians. Juvenile HV deformity is a common presentation, and digital photography offers a means of avoiding unnecessary repeated exposure to ionizing radiation in individuals whose HV angle may need to be monitored over a long period of time. A secondary benefit of having a digital image on record is that it can be used retrospectively to show progress to the patient. This can be a powerful motivational tool to assist with treatment compliance. Finally, while digital imaging and processing software is becoming widely utilized in healthcare settings, future development of smartphone applications could combine the image capture and measurement procedure into a single step, thus streamlining the method for convenience of both clinicians and researchers.

CONCLUSION

This study demonstrates that digital photographs taken under standardized conditions can be used with confidence to measure HV angle as these measurements accurately represent joint angle compared to the current criterion standard of weight-bearing dorsoplantar foot radiographs. Validity data were also supported by good intrarater and interrater reliability. One of the main advantages to this method of HV angle measurement is that it provides an inexpensive and non-invasive alternative to radiographs, while providing a more incremental measure of HV progression than commonly used categorical rating scales. Further research is warranted to validate this procedure for use in a clinical setting.

KEY POINTS

Findings: Measurements of HV angle can be performed with acceptable reliability and validity using standardized digital photographs.

Implication: Compared to clinical rating scales currently used to classify HV severity, digital photographs provide a more incremental measure of hallux deviation, and may reduce the need for radiographs in early stages of monitoring HV deformity.

Caution: Determining reference points on digital photographs may be dependent upon examiner experience and knowledge of surface anatomy. Subject positioning and camera placement must be standardized to reduce potential error.

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TABLES

TABLE 1. Intrarater reliability of HV angle measurements (76 feet)

Image	Test*	Retest*	$ICC_{3,1}$ (95% CI)	SEM (°)	MDC_{90} (°)	RC (°)
Radiograph	22.2 ± 10.6	21.7 ± 10.2	0.99 (0.99 to 1.0)	1.1	2.5	± 2.9
Photograph	23.2 ± 10.1	22.6 ± 9.9	0.97 (0.95 to 0.98)	1.8	4.1	± 5.3

Abbreviations: HV, hallux valgus; ICC, intraclass correlation coefficient; CI, confidence interval; SEM, standard error of measurement; MDC_{90}, minimal detectable change (at 90% confidence level); RC, repeatability coefficient.
* Values presented are mean ± SD (°).

TABLE 2. Interrater reliability of HV angle measurements (40 feet)

Image	Examiner 1*	Examiner 2*	$ICC_{2,1}$ (95% CI)	SEM (°)	MDC_{90} (°)	RC (°)
Radiograph	19.7 ± 10.4	20.4 ± 10.8	0.99 (0.98 to 1.0)	1.0	2.4	± 3.0
Photograph	21.0 ± 10.1	21.1 ± 11.0	0.96 (0.93 to 0.98)	2.0	4.7	± 5.8

Abbreviations: HV, hallux valgus; ICC, intraclass correlation coefficient; CI, confidence interval; SEM, standard error of measurement; MDC_{90}, minimal detectable change (at 90% confidence level); RC, repeatability coefficient.
* Values presented are mean ± SD (°).

TABLE 3. Validity of photographic HV angle measurements compared to radiographs

Examiner	Radiograph*	Photograph*	MD (95% CI) (°)	*P* value	95% LA (°)	MAD (°)	Pearson's r
Examiner 1 (76 feet)	21.6 ± 10.1	22.7 ± 9.9	-1.0 (-3.3 to 1.2)	0.37†	-6.5 to 4.4	2.5	0.96
Examiner 2 (40 feet)	20.4 ± 10.8	21.1 ± 11.0	-0.7 (-5.5 to 4.1)	0.77†	-4.9 to 3.5	1.9	0.98

Abbreviations: HV, hallux valgus; MD, mean difference; CI, confidence interval; LA, limits of agreement; MAD, mean absolute difference.

* Values presented are mean ± SD (°).

† T-tests indicated no significant difference ($p > 0.05$).

TABLE 4. Comparison of limits of agreement by subgroups of age and HV severity (76 feet)

Subgroups	Radiograph*	Photograph*	MD (95% CI) (°)	*P* value	95% LA (°)
Aged ≤ 50 years (30 feet)	18.5 ± 9.1	19.6 ± 9.3	-1.1 (-4.5 to 2.2)	0.51†	-5.8 to 3.6
Aged > 50 years (46 feet)	23.7 ± 10.2	24.7 ± 9.8	-1.0 (-3.9 to 2.0)	0.51†	-6.8 to 4.9
None/mild HV (36 feet)	15.1 ± 8.5	16.6 ± 8.2	-1.5 (-4.2 to 1.3)	0.29†	-6.2 to 3.2
Moderate/severe HV (40 feet)	27.6 ± 7.3	28.2 ± 7.8	-0.6 (-3.0 to 1.8)	0.61†	-6.6 to 5.4

Abbreviations: HV, hallux valgus; MD, mean difference; CI, confidence interval; LA, limits of agreement.
* Values presented are mean ± SD (°).
† T-tests indicated no significant difference ($p > 0.05$).

FIGURES

FIGURE 1. A standardized procedure was used for obtaining radiographs and digital photographs. Participants were positioned in their angle and base of gait. The x-ray tube distance (100cm) and angle (15 degrees from vertical) also determined the position of the digital camera.

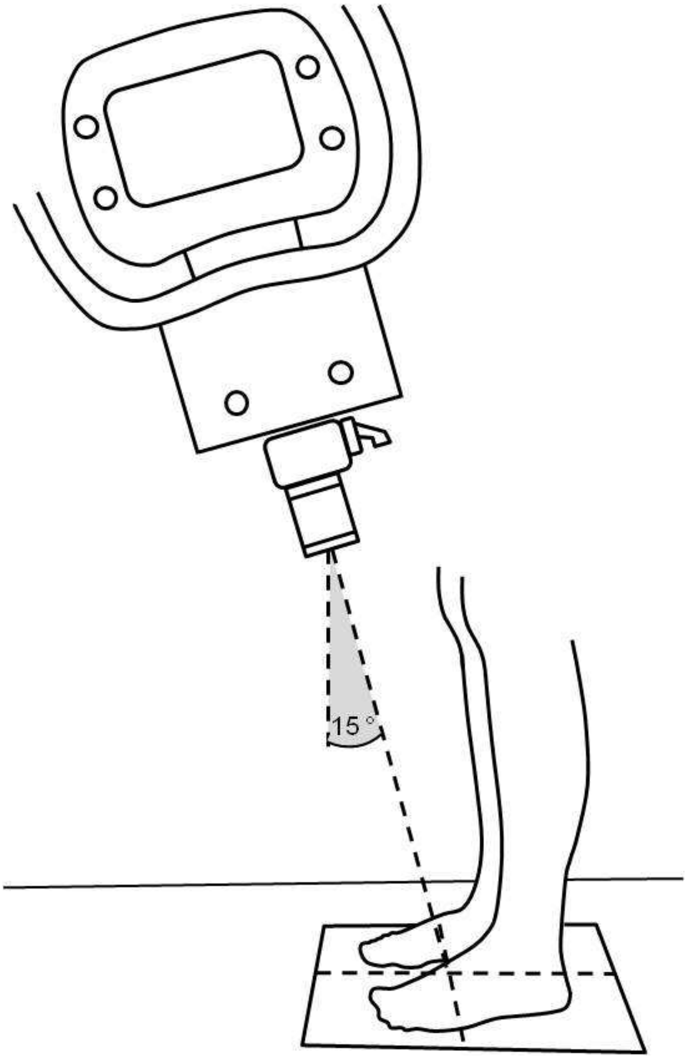

FIGURE 2A-B. Standard reference points were used to measure the angle between the hallux and first metatarsal shaft (hallux valgus angle) on digital photographs (A) and radiographs (B). Points *a* and *b* mark visual bisection points at the distal and proximal shaft of the proximal phalanx. Point *c* represents the centre of the first metatarsal head, and *d* marks a visual bisection of the proximal first metatarsal shaft. X marks the intersection of the 2 axes: *a*-*b* and *c*-*d*. Reference points on radiograph are at the medial and lateral cortex in the metaphyseal/diaphyseal regions of the first metatarsal and proximal phalanx.