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SCIENTIFIC ARTICLE

3D hindfoot alignment measurements based on low-dose biplanar radiographs: a clinical feasibility study

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Abstract

Objective To test a 3D-hindfoot alignment (HA) measurement technique based on low-dose biplanar radiographs (BPRs) in a clinical setting and compare the results with 2D-HA measurements on long axial view radiographs (LARs).

Materials and methods This prospective study was approved by the local institutional review board. HA measurements on 3D-BPR and 2D-LAR of 50 patients (29 female; mean age 47 ± 16.6 years) were compared (positive values = valgus; negative values = varus). Two independent musculoskeletal radiologists (readers 1 and 2) performed 3D-HA measurements on BPR using a custom-made MATLAB code and measured HA on LAR during two separate readout sessions. Descriptive statistics and intraclass correlation coefficients (ICC) were calculated, and Bland–Altman plots were used for intermethod comparison.

Results Using BPRs, HA was 0.8° ± 9.°1 (range, −20.2 to 20.0) for reader 1, and 0.7° ± 9.5° (range, −21.2 to 18.3) for reader 2. HA on LARs was −2.0 ° ± 7.0° (range, −27.0° to 11.1°) for reader 1 and − 1.7° ± 7.0° (range, −24.1° to 14.3°) for reader 2. Interreader agreement for measurements was excellent, both for BPRs (ICC = 0.992; 95% CI:0.986–0.995) and LAR measurements (ICC = 0.962; 95% CI:0.932–0.978). Mean difference between the two methods was −2.43° (range, −29.4° to 25.6°) for reader 1 and −2.6° (range,-28.7° to 30.2°) for reader 2. On Bland–Altman plots, three measurements of reader 1 and six measurements of reader 2 were outside of the ±1.96 SD interval.

Conclusion Hindfoot alignment measurements on 3D-BPR have an excellent interreader agreement in a clinical setting. Large measurement errors can occur in individual patients using 2D-LAR alone. Therefore, we suggest using 3D-BPR measurements in daily routine for the assessment of HA, which are independent of rotational foot malpositioning.

Keywords Biplanar radiographs · Hindfoot · Alignment · Long axial view · Ankle

Introduction

Hindfoot alignment (HA) is an important determinant in many congenital and acquired abnormalities of the foot that go along with hindfoot varus or valgus malalignment [1, 2]. An accurate assessment of HA is crucial for the orthopedic surgeon, as clinical assessment alone lacks sufficient quantification and objectivity. Furthermore, hindfoot malalignment has been identified as an important risk factor for stress fractures, ankle sprain, tendinitis, and ankle instability [2–5]. The hindfoot angle is defined as the angle between the mid-calcaneal long axis and the midline of the body (respectively, the mid-tibial long-axis) [6], for illustration see Fig. 3 in Sutter et al. [7].

During the last few decades, several different image-based HA measurements have been introduced into the radiological and orthopedic literature, but accurate measurements remain a technical challenge concerning image acquisition and measurement technique [3, 8–11]. Most commonly, the measurements are performed on so-called "long axial view" radiographs. This view is achieved by a standing patient position with the X-ray beam angled at 45° to the floor/film cassette (see Fig. 1) [12]. The measurements on these radiographs, however, are characterized by a low interreader reliability [12, 13]: interreader differences in individual cases can be as large as the physiological range of the normal hindfoot angle (which is 0° to 10° valgus). With such large differences, measurements of one reader may indicate a normal hindfoot axis and those of a second reader based on the same images a pathological one, potentially resulting in an inaccurate diagnosis and treatment.

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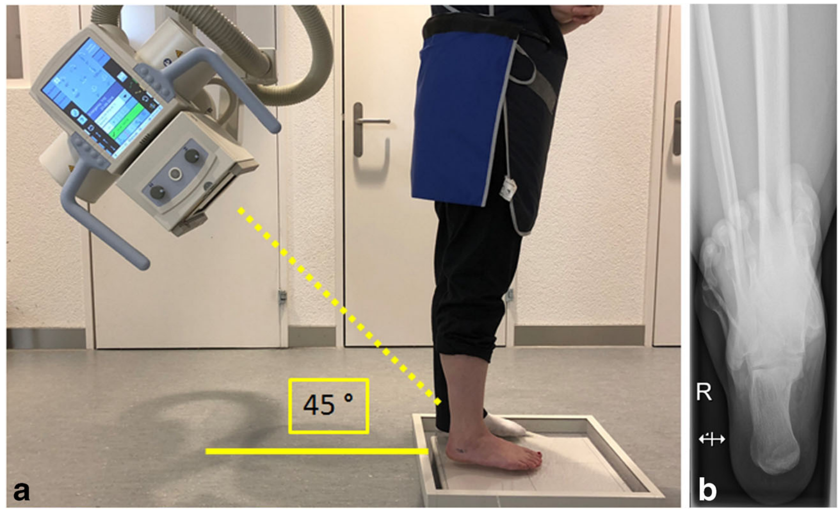

Fig. 1 **a** Correct positioning for long axial view radiographs (LARs), with the central X-ray beam angled at 45° toward the cassette/floor. **b** Accurate LAR in a 25-year-old female patient

Measurements using computed tomography require a substantially larger radiation dose than with conventional radiographs and are laborious: it is difficult to define and reconstruct the calcaneal and tibial axis in a 3D dataset—and reconstruction is time-consuming. Furthermore, normal CT images are produced in a supine position and therefore may be inaccurate, as foot alignment changes in a weight-bearing position [14]. However, a recently published CT study in a weight-bearing position was shown to be reproducible and objective in the assessment of HA [15]. However, CT machines that allow image acquisition in a standing position are not widely distributed and available.

A new measurement technique using 3D reconstructions based on biplanar radiographs (BPRs) has been introduced recently [7]. This technique allows image acquisition in a weight-bearing position with a very low radiation dose and proved to be reliable and independent of foot malpositioning in phantoms [7, 16, 17]. However, to our knowledge, there have been no publications that evaluate this technique in patients in a clinical setting so far.

Therefore, the purpose of this study was to evaluate this new technique in daily routine in patients referred from an orthopedic outpatient clinic and to compare the results with state-of-the-art measurements on long axial view radiographs (LARs).

Materials and methods

This prospective study was approved by the local institutional review board. Informed consent was obtained from all patients.

All patients from our university hospital outpatient clinic referred for LARs and HA measurement between July 2014 and May 2016 were included in this study.

Patients with a history of previous foot surgery or fracture and patients younger than the age of 18 were excluded. Furthermore, patients with known or suspected pregnancy were not imaged and therefore excluded from the study.

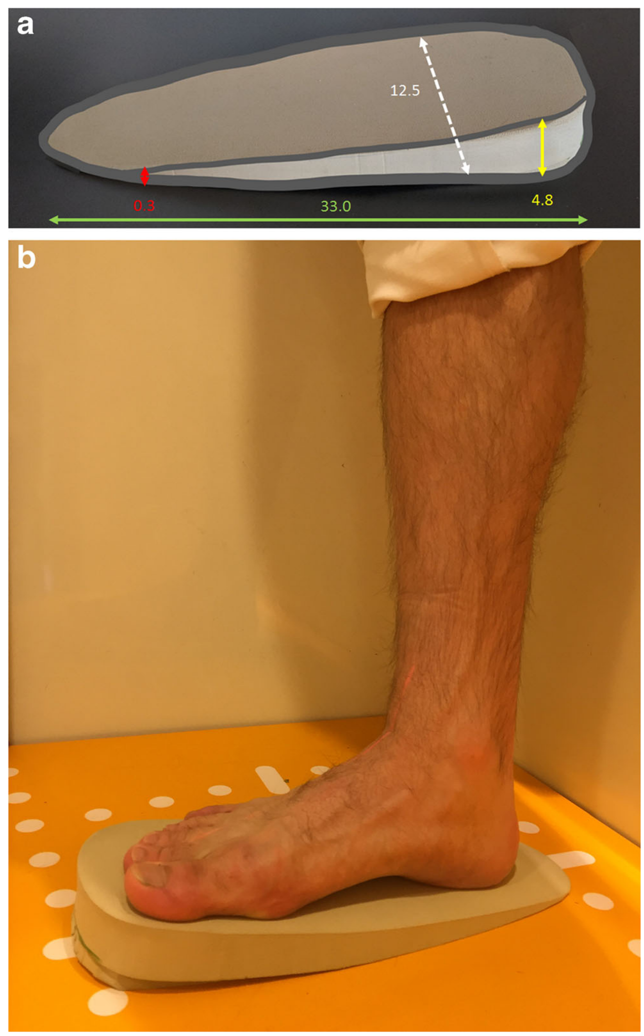

Fig. 2 **a** Drawing showing the diameters (in centimeters) of the plastic wedge that was put under the foot during the biplanar radiograph (BPR) scans: height posterior (*red*), height anterior (*yellow*), width (*white*), and length (*green*). **b** Patient's position during BPR scanning with underlying plastic wedge. The patient was standing on one foot during the image acquisition

In total, 50 patients (29 female, 21 male) were included in this prospective study research. The age range of the patients was 18–81 years (mean 47 ± 16.6 years).

All the study patients included were scanned with BPRs and with LARs on the same day.

Measurements on biplanar radiographs

All patients were examined in a low-dose biplanar X-ray scanner (EOS imaging system; EOS Imaging, Paris, France). An anteroposterior image (tube voltage, 85 kV; tube current, 160 mA) and a lateral image (tube voltage, 80 kV; tube current, 100 mA) were acquired simultaneously in a standardized, weight-bearing examination position. For better visualization of calcaneal contours on the anteroposterior image, a plastic wedge was placed under the forefoot in each patient during image acquisition (Fig. 2). During the acquisition, the patients were standing on one leg only, and stabilizing themselves by grasping a horizontal handle bar with their hands.

Postprocessing of BPR data was performed using a manufacturer-specific software (sterEOS software, EOS imaging system; EOS Imaging). This software allows for unequivocal identification of a point in space defined by its projection on the two perpendicular biplanar images (anteroposterior and lateral images). HA was then measured based on the specific anatomical landmarks of the hindfoot (Fig. 3a, b): the detailed reconstruction process was previously described by Sutter et al. [7]. After saving the BPR with annotated reference lines and points needed for HA measurement in Digital Imaging and Communications in Medicine (DICOM) format, the data were analyzed using a custom-made MATLAB code (Mathworks, Natick, MA, USA): this code automatically calculates the HA angle based on the tibial shaft axis, the hindfoot axis, and compensates for possible rotational malalignment of the foot at the occasion of image acquisition by projecting this angle on a defined coronal plane using a 3D projection (Fig. 3c).

Postprocessing and all measurements were performed by two fellowship-trained musculoskeletal radiologists (reader 1 and reader 2).

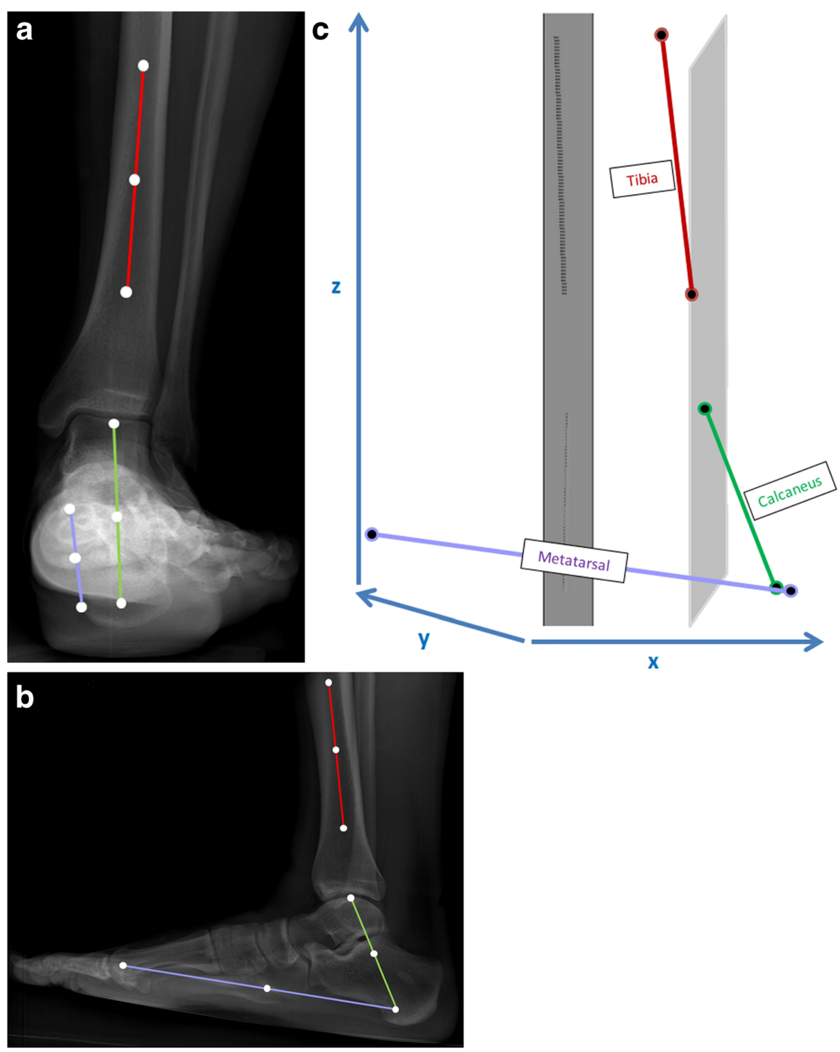

Fig. 3 **a** Anteroposterior view and **b** lateral view of acquired BPR images in a 25-year-old male patient with anatomical landmarks placed by reader 1 defining the tibial shaft axis, the metatarsal line (connecting the medial head of the first metatarsal bone to the calcaneus), the calcaneal axis (connecting the trochlea tali with the calcaneus). Hindfoot alignment (HA) was calculated as 9 ° valgus. **c** Corresponding visual output of the 3D reconstruction using a custom-made MATLAB code

Measurements on long axial view radiographs

Long axial view radiographs were acquired from all patients. All measurements were performed by the same musculoskeletal radiologists (reader 1 and reader 2).

Long axial view radiographs were acquired using a fully digital radiography system (Ysio; Siemens Healthcare, Erlangen, Germany) as described in Reilingh et al. [12] with a tube-detector distance of 1.5 m, tube voltage 50 kV, tube load of 4.1 mAs, X-ray beam tilt of 45° in the craniocaudal direction and with the foot placed on top of the detector plate with the medial contour of the foot parallel to the X-ray beam [3, 12].

Hindfoot alignment was quantified on the radiographs by measuring the angle between the tibial shaft axis and the calcaneal axis (Fig. 4) [13]. The tibial shaft axis was defined as follows: the line connecting the midpoints of two pairs of points on the cortex of the distal tibia. Between these two pairs of points, a minimum distance of 3 cm was maintained. The calcaneal axis was defined as follows: the line connecting the midpoint between the lateral edge of the calcaneus at the level of the subtalar joint and the corner at the inferior aspect of the sustentaculum base, and the midpoint between the medial and lateral contour of the posterior calcaneal process.

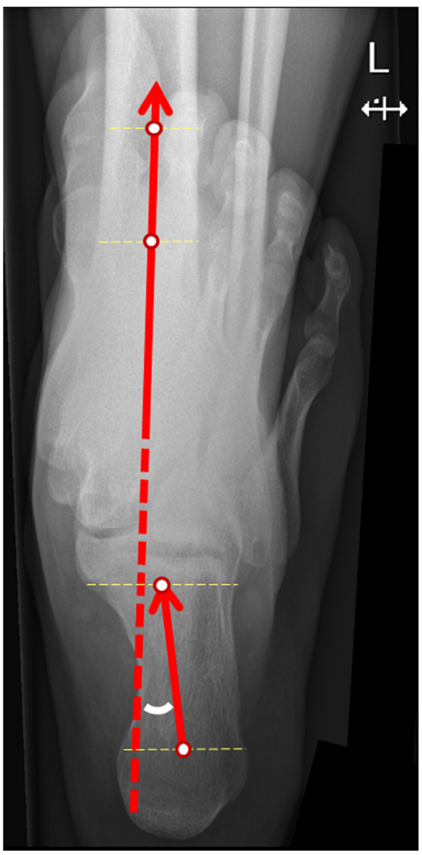

Fig. 4 Detailed HA measurements (white angle; 5° valgus) on LAR in the same patient as in Fig. 3. The tibial shaft axis was defined by a line connecting the center of two pairs of points (*white dots with a red circle*) that are lying in the midpoint of two accessory lines (*yellow dotted lines*) that run from the medial to the lateral cortex of the distal tibia. A minimum distance of 3 cm was maintained between these two pairs of points. The calcaneal axis was defined as a line connecting the midpoint (*white dot with red circle*) between the lateral edge of the calcaneus at the level of the subtalar joint (*anterior yellow dotted line in the calcaneus*) and the corner at the inferior aspect of the sustentaculum base, and the midpoint (*white dot with red circle*) between the medial and lateral contour of the posterior calcaneal process (*posterior yellow dotted line in the calcaneus*)

Statistical analysis

Descriptive statistics were used for comparison of HA. Interobserver agreement and agreement between the two methods were quantified by calculating the intraclass correlation coefficients (ICCs). ICC values were interpreted as follows: less than 0.40 = poor; between 0.40 and 0.59 = fair, between 0.60 and 0.74 = good, and between 0.75 and 1.00 = excellent. All analyses were performed using statistical software (SPSS for Windows, release 23.0; SPSS, Chicago, IL, USA).

Results

Positive measurement values were used for valgus, and negative values for varus HA.

Measurements on biplanar radiographs

Mean hindfoot angle measurement using BPR was 0.8° ± 9.1° (range, −20.2° to 20.0°) for reader 1, and 0.7° ± 9.5° (range, −21.2° to 18.3°) for reader 2.

Mean interreader difference (R1-R2) was 0.07° ± 1.7° (range, −6.2° to 4.1°). Interreader agreement for BPR measurements was excellent, with an ICC value of 0.992 (95% confidence interval: 0.986–0.995).

Measurements on long axial view radiographs

Mean hindfoot angle measurement on LAR was −2.0 ° ± 7.0° (range, −27.0° to 11.1°) for reader 1 and −1.7° ± 7.0° (range, −24.1° to 14.3°) for reader 2.

Mean interreader difference (R1-R2) was 0.2° ± 2.7° (range, −5.3° to 6.7°). Interreader agreement for measurements was excellent, with an ICC value of 0.962 (95% confidence interval: 0.932–0.978).

Intermethod agreement: BPR versus LAR

Intermethod agreement was good with an ICC value of 0.66 (−0.646 to 0.470). The mean difference between the two methods was −2.4° (range −29.4° to 25.6°) for reader 1 and −2.6° (range −28.7° to 30.2°) for reader 2. On Bland–Altman plots three measurements of reader 1 and six measurements of reader 2 were outside of the ±1.96 SD interval. With increasing mean values of the LAR and BPR measurements, no trend toward an increase or decrease in the differences between the two methods could be found.

For more details see Bland–Altman plots in Fig. 5.

Discussion

The current clinical "standard" for assessment of HA is based on 2D-radiographic measurements: the preferred method employs 2D-LARs as these are more reliable and have a better interreader agreement than measurements based on HA view radiographs [12, 13].

However, a recent study using foot phantoms found that measurements using these 2D-long axial views are very dependent on the correct foot positioning [7] regarding internal and external rotation, which is sometimes hard to achieve in patients with foot pain, movement restrictions, and foot deformations. The same publication showed that 3D-BPR measurements are almost independent of foot rotation and therefore more reliable for the assessment of the correct hindfoot axis. The current study evaluates

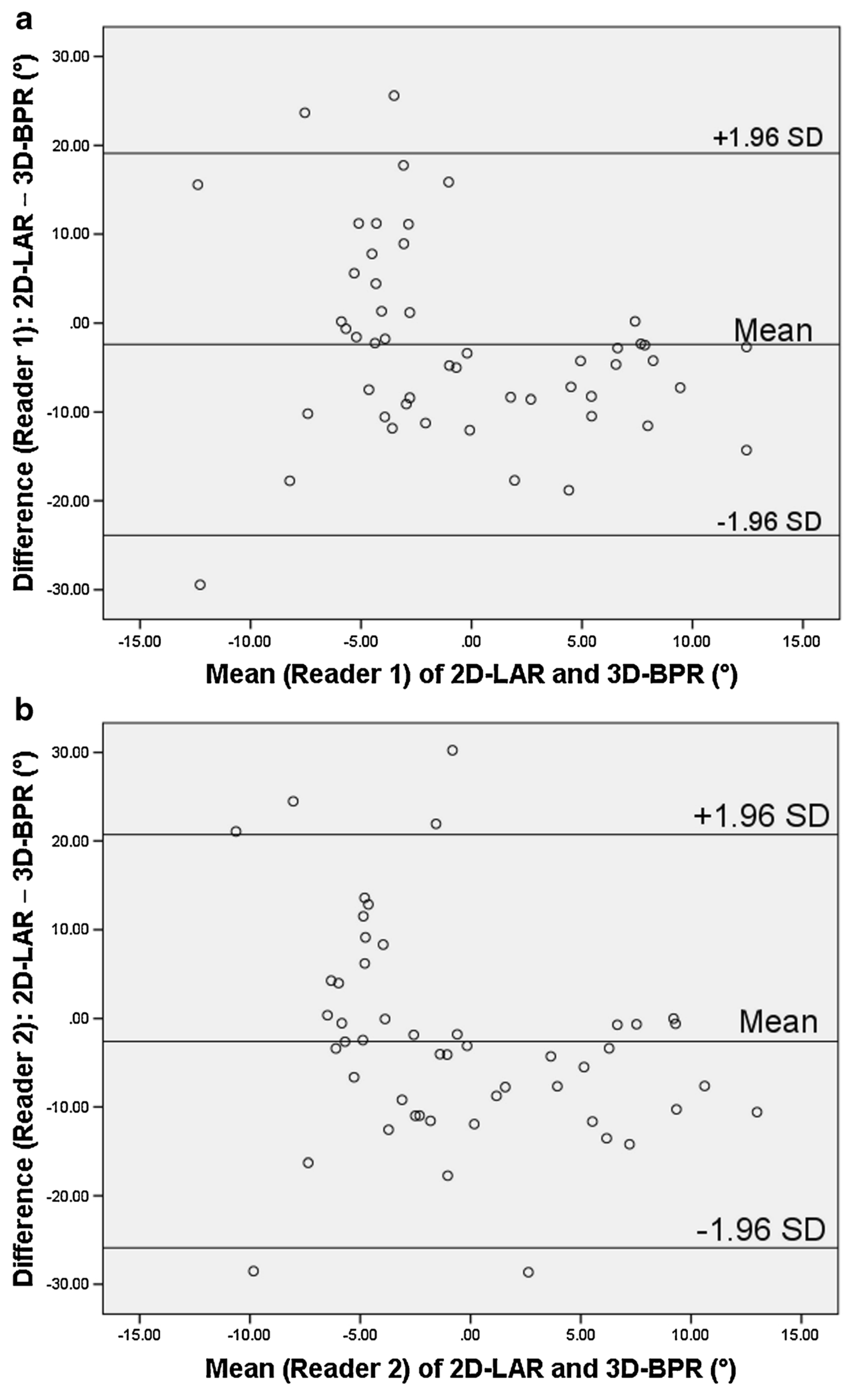

Fig. 5 **a** Bland–Altman plots of measurements by reader 1 showing the differences between HA measurements with 2D-LAR- and 3D-BPR-based measurements. **b** Bland–Altman plots of measurements by reader 2 showing the differences between HA measurements with 2D-LAR- and 3D-BPR-based measurements

whether those ex-vivo results can be confirmed in a prospective clinical setting with patients referred for foot problems with suspected abnormalities of the hindfoot axis.

The excellent interreader agreement for both 3D-BPR and 2D-LAR measurements in our study is similar to the ICC values found in the phantom study by Sutter et al. (ICC = 0.926–0.995) [7]. Other clinical studies found slightly lower ICC values for interreader agreement regarding hindfoot measurements on LAR (e.g., ICC = 0.79 by Reilingh et al. [12]), which may be explained by the greater experience of our readers (the two readers were fellowship-trained senior staff radiologists whereas in the study by Reilingh et al. residents also measured the hindfoot angles). The Bland–Altman plots in our study showed overall comparable measurement results between 3D and 2D measurements, but we found severe statistical outliers in 9 patients. Looking in more detail, those outliers consisted of differences between LAR and BPR measurements of up to 30° valgus and 29° varus, and are probably caused by malpositioning of the foot on LAR images due to accidental external or internal rotation. Sutter et al. found similar outliers on LAR measurements in phantoms for varus alignment (up to 27°), but with lower discrepancies (maximum 14°) for valgus alignment. Those wrong measurements on LAR could be catastrophic in individual patients and could lead to incorrect treatment if the referring surgeon's assessment relies on those measurements only. The disadvantage of 3D-BPR measurements is of course the overall time interval from image acquisition to the final measurement result, as the postprocessing part alone takes about 2 min [7].

We did not compare radiation dose for the two imaging methods as the foot is an area with low sensitivity to radiation and published data in literature showed negligible radiation dose results for both imaging methods [17, 18]. In general, low-dose BPR images have a lower (overall) radiation dose compared with a normal X-ray, although two images are acquired simultaneously [16, 17].

A limitation for our study is the lack of correlation of our measurements with the referring physician's clinical assessment, intraoperative findings or other modalities (e.g., corresponding CT images in a weight-bearing position).

In conclusion, our data confirm the comparability of 3D-BPR measurements with the "standard" 2D-LAR measurements for HA assessment. However, because large measurement errors can occur in individual patients using LAR alone, we suggest using 3D-BPR measurements in daily routine as the first choice for the assessment of HA measurements whenever possible and available.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflicts of interest. The authors did not receive any financial benefits from EOS.

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