Chapter 9
Normal Hindfoot Alignment Assessed by Weight Bearing CT: Presence of a Constitutional Valgus?

Introduction

Hindfoot alignment has classically been determined using a long axial or hindfoot alignment view [1]. Studies using these radiographic methods in normal asymptomatic feet report values between 2° and 5° of valgus in the general population [2]. Clinical measurements of the hindfoot are situated between 5.61° and 6.50° of valgus [3]. These findings give the impression of a physiological valgus alignment of the hindfoot. However, results are based on small cohorts [2, 4], lack a clear correlation between clinical/radiographical data [5], and impose important measurement errors due to bony superposition present in plane weight bearing radiographs [6]. The latter is currently overcome by the use of weight bearing CT which provides an accurate bone position and allows a natural stance of the patient [7]. Various methods now have been described to determine hindfoot alignment using weight-bearing CT [7, 8]. This study will use a method composed out of the anatomical axis of the tibia and the talocalcaneal axis based on the inferior point of the calcaneus as described previously [9]. To investigate not only the radiological relevance of this point but also a possible biomechanical role, a density analysis will be performed. An increased ossification around the inferior point would indicate a higher load application as stated by Wolff's law [10]. Currently the measurement method was only used in malalignments of the hindfoot and lacks reference values. Therefore, the goal of this study is to obtain measurements from a population with clinical and radiological absence of hindfoot pathology. These will be compared to hindfoot measurements obtained from the long axial view based on the anatomical axis of the tibia and the calcaneal axis, to point out possible differences attributed to the measurement method [1]. Although surgical hindfoot corrections are frequently performed either extra-articular by osteotomies or intra-articular by arthrodesis, still

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numerous debate exists on the amount of correction and the ideal foot position after arthrodesis [11, 12]. Per-operative tools are already used to obtain a more accurate correction [13] or a physiological load distribution [14], but a preoperative planning remains paramount. This study will contribute to the preoperative planning by providing further insights into a physiological hindfoot alignment. The null hypothesis is the existence of an overall physiological valgus alignment in the hindfoot.

Materials and Methods

Study Population and Design

Forty-eight patients, mean age of 39.6 ± 13.2 years, with clinical and radiological absence of hindfoot pathology were included. Indications for imaging consisted out of minor foot and ankle trauma with persistent complaints in purpose to rule out an occult fracture, but appeared to be negative or nonsignificant ($n = 31$), suspicion of osteoartrosis but not detectible on weight bearing CT imaging ($n = 11$), and MTP I fusion to assess consolidation ($n = 4$) (Table 9.1).

Patient Characteristics

Each time the contralateral not affected foot was used for analysis. This was performed using CurveBeam® software applied on the images retrieved from the weight bearing CT (pedCAT®). Ethical committee gave permission in performing the study (OG10601102015). Following imaging protocol was used: radiation source was set at 4 mAs and 50 kV, with a focus distance of 100 cm, with the beam pointed at the ankle joint. PedCAT used the following settings: tube voltage, 96 kV; tube current, 7.5 mAs; CTDIvol 4.3 mGy; matrix, 160,160,130; pixel size, 0.4 mm; and slice interval 0.4 mm. At the department of radiology, patients were asked to attain a natural stance with both feet parallel to each other and straight ahead at shoulder width.

Hindfoot measurements were performed by two authors AB and EDV. Each measurement was repeated three times; after the complete set of measurements, the mean out of three measurements was used for further analysis. The hindfoot angle was

Table 9.1 Patient characteristics

Characteristic	Total (N = 48)
Age (±) SD	39.6 ± 13.2 years
Sex (M/F)	28/20
Minor trauma	31
Absence osteoarthritis	11
MTP I fusion	4

determined based on the inferior point of the calcaneus (HA_{IC}) as described previously [9]. In brief the foot is positioned according to the second ray, and the angle is composed out of the intersection between the anatomical tibial axis (TA_x) and the talocalcaneal axis (TCA_x) (Figs. 9.1a and 9.2a). The latter is formed by connecting the inferior point of the calcaneus with the middle of the upper surface of the talus (Fig. 9.3a, b). This will be compared to the hindfoot angle measured on the long axial view (HA_{LA}), for which firstly the foot needed to be aligned with second ray and inclined 45° by applying the reconstruction mode built in to the used software (Figs. 9.1b and 9.2b, c). Secondly the calcaneus needed to be divided 50–50% in the

Fig. 9.1 (**a**) Overview of the measurement method (HA_{IC}) based on the inferior calcaneal point (lower right quadrant) after alignment of the foot according to second ray (upper right quadrant, green line) (**b**). In comparison to the long axial method (HA_{LA}) based on dividing the calcaneus (lower right quadrant) after inclination of the feet towards 45° and aligning with the second ray (upper right quadrant, green line)

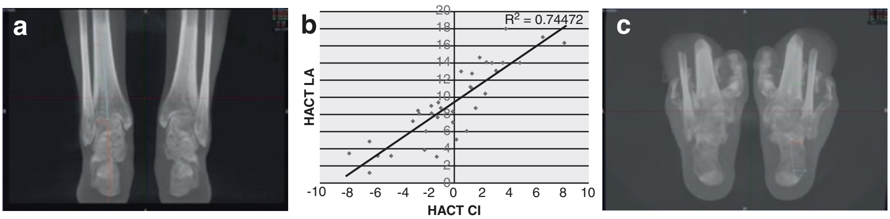

Fig. 9.2 (**a**–**c**) Correlation between both measurement methods showed to be good with an $R^2 = 0.74$, indicating that both can be used to determine hindfoot alignment but with higher valgus values obtained in the HA_{LA}

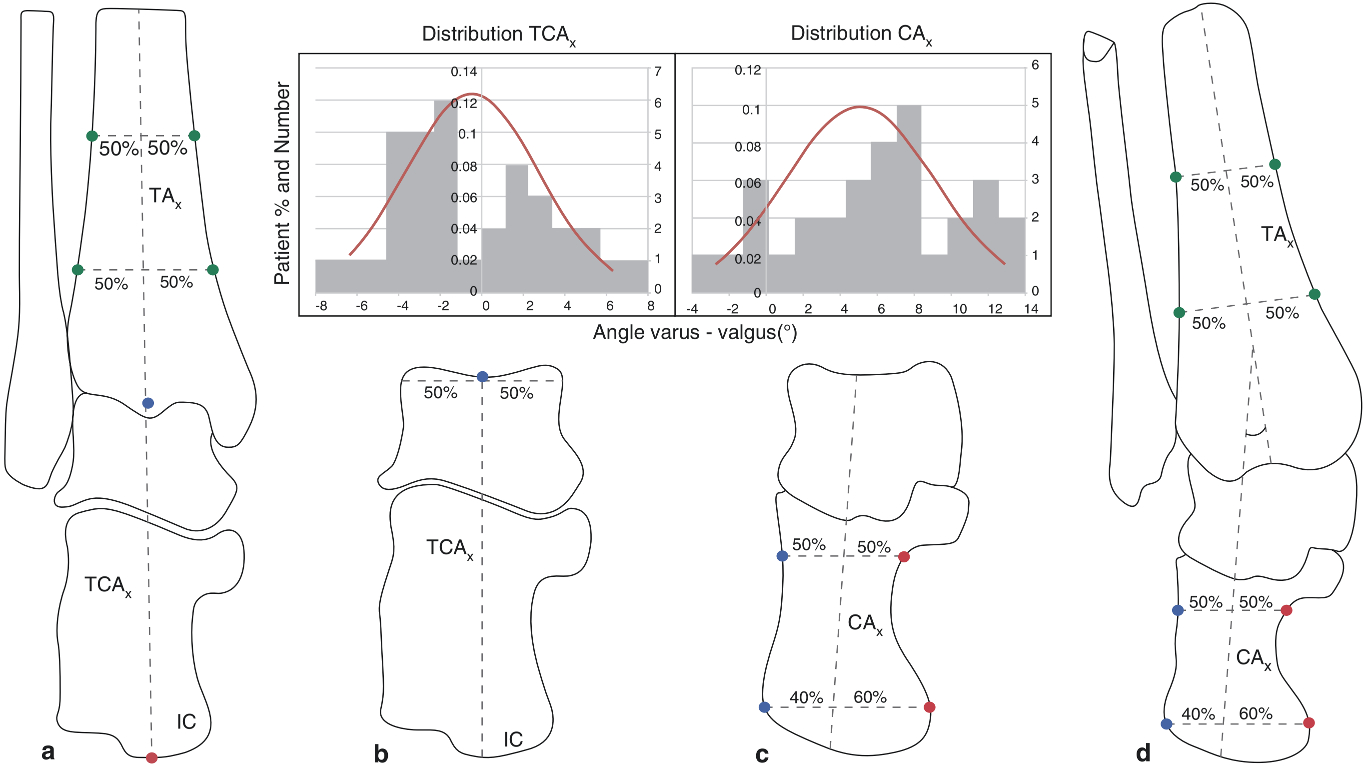

Fig. 9.3 Schematic overview of both hindfoot measurement methods (**a**). HA_{IC} composed out of the anatomical tibia axis (TA_x), by dividing the tibia shaft 50–50% each one third (green points) and talocalcaneal axis (TCA_x) by connecting the inferior calcaneus point (IC, red point) with the middle of the talar dome (blue point) (**b**). Distribution of the (TCA_x) (**c**). Distribution of the (CA_x) pointing out a shift towards a valgus value (**d**). HA_{LA} composed out of the anatomical tibia axis (TA_x) and the calcaneal axis (CA_x) after dividing the calcaneus and inclining the foot 45°

upper part and 40–60% in the lower part to determine the calcaneal axis (CA_x) as described by van Dijk et al. [1] (Fig. 9.3c). The HA_{LA} was composed out of the intersection between the TA_x and the CA_x on the inclined foot (Fig. 9.3d).

To investigate the relevance of the inferior calcaneus point, a bone density analysis was performed by calculating the pixel density of this region of interest (ROI) in the coronal plane and comparing it to a regional area with the same surface window by using an OsiriX®-based plug in software (Fig. 9.4a, b). A higher pixel density would concur with an increased calcium/bone density, and by applying Wolff's law, this would indicate a higher load exposure [10]. To avoid the influence of traction exerted by the fascia plantaris on the bone formation in this inferior calcaneal region, the ROI was set at a distance of 5 mm from the medial calcaneal tuberosity in the sagittal plane (Fig. 9.4c, d).

Hindfoot characteristics in the tibiotalar joint were measured as the talar tilt (TT) and the tibial inclination (TI) of the articular surface towards the horizontal axis as described previously [9]. In the subtalar joint the subtalar vertical angle (SVA) was measured in the middle coronal plane when started at the level of the highest point of the talar dome according to the method described by Knupp et al. [15]

Statistical Analysis

A Kolmogorov-Smirnov test was used to analyze if the data were normally distributed. Depending on the outcome, a parametric Student's t-test or a nonparametric Wilcoxon signed rank test will be conducted to compare the means of the two used hindfoot angles. Regression analysis was performed to correlate the relative change of both angles by calculation of the Spearman's coefficient and visualization of a corresponding scatterplot. To assess the density analysis between the inferior calcaneus point and the regional calcaneal area, the dependent Student's t-test was used. Inter- and intraobserver variability of the obtained measurements was analyzed using interclass correlation coefficient (ICC). This was interpreted as follows: $ICC < 0.4$, poor; $0.4 < ICC < 0.59$, acceptable; $0.6 < ICC < 0.74$, good; and $ICC > 0.74$, excellent [16]. The SPSS (release 20.0.0. standard version, SPSS, Inc., Chicago, IL, USA) statistical package was used to analyze the results. A probability level of $P < 0.05$ was considered significant.

Results

Hindfoot Alignment

Kolmogorov-Smirnov analysis shows a $P > 0.05$ for both hindfoot parameters indicating that the measurements are normally distributed, and therefore further parametric testing could be used. The mean HAIC equaled 0.79° of valgus ± 3.2 with a

Fig. 9.4 (**a**) 3D overview (**b**). Density of the WBC compared to the regional calcaneal area (**c**). ROI was set at a distance of 5 mm from the medial calcaneal tuberosity to avoid bone formation by traction influence of the fascia plantaris (**d**). Measurement of the hindfoot angle based on the osteosclerotic weight bear point (WBC) of the calcaneus

Table 9.2 Mean hindfoot measurements in degrees and concomitant intraclass correlation coefficients

	Hindfoot measurements	SD (±)	ICC_{inter}	ICC_{intra}
HA_{IC}	0.79	3.2	0.73	0.81
TA_X	2.7	2.1	0.76	0.83
TCA_X	0.61	2.9	0.85	0.82
HA_{LA}	9.1	4.8	0.71	0.74
TA_X	3.8	2.9	0.81	0.78
CA_X	5.2	4.1	0.71	0.79
TI	2.4	0.84	0.81	0.86
TT	1.9	0.86	0.83	0.82
SVA	96.1	5.7	0.73	0.76

mean TACT of 2.7° varus ± 2.1 and a mean TCAx of 0.61° varus ± 2.9 (Table 9.2, Figs. 9.2a and 9.3). The mean HALA equaled 9.1° of valgus ± 4.8° with a mean TAx of 3.8° varus ± 2.9 and a mean CAx of 5.2° valgus ± 4.1.

Comparing both pointed out that HALA was significantly different $P < 0.001$ from the HAIC by showing an increased valgus value (Tables 9.2 and 9.3), whereas the HAIC showed a more neutral alignment (Figs. 9.2 and 9.3). Correlation between both was shown to be good by a Spearman's correlation coefficient = 0.74.

Table 9.3 Results of independent Student t-testing

	HACT $_{CT\ IC}$/HA$_{CT\ CL}$	ROIcalc med/ROIcalc lat
t-value	<0.001	<0.001
P-value	<0.001	<0.001

ROI Density Analysis

The mean density of the WBP equaled 271.3 ± 84.1 and was significantly higher than the regional lateral calcaneal area 109.4 ± 63.2 ($P < 0.001$).

Hindfoot Characteristics

Measurements in the tibiotalar joined showed a mean TI = 1.9° ± 0.81° and a mean TT = 2.4° ± 0.86°. Measurements in the subtalar joint showed a mean SVA = 96,1° ± 5.7°.

Discussion

This study shows a more neutral alignment of the hindfoot when applying the measurement method based on the inferior point of the calcaneus (HAIC). Therefore, the anatomical tibia axis and the inferior point as described by Saltzman in the hindfoot alignment view were used [17]. Additionally, the talus was incorporated in the measurement method, as an important component of the hindfoot and due to its visibility on weight bear CT, as opposed to plane weight bear radiographs, where it's often superimposed by the midfoot [1, 17, 18]. The obtained results couldn't retain the null hypothesis of a physiological valgus alignment in the hindfoot as reported by previous literature [2, 3]. This can be attributed to either the used measurement method or to a physiological neutral configuration of the talus and calcaneus towards the tibia. Previous studies and this study show that by using a measurement based on dividing the calcaneus (HA$_{LA}$), an increased valgus alignment will be obtained [12]. Additionally, it is pointed out that by altering the foot position towards an increased endo-rotation, an overestimation of the valgus alignment occurs [12, 19, 20]. This advocates using the inferior calcaneus point, as it requires no additional steps, such as dividing the calcaneus in half, and hence avoiding possible measurement errors. Another relevance of the inferior weight bear point is shown by the presence of an increased bone formation as shown by the pixel density analysis suggesting an increased load exposure when following Wolff's law [10]. This makes it an interesting landmark as a reference point when planning an osteotomy, considering that the goal of this procedure is to shift the load towards a biomechanical more favorable position [13, 21]. An important disadvantage of the used method is the absence of complete 3D measurement. Although each foot was positioned using the same method according to three planes, the actual hindfoot angle was only determined in the coronal plane, possibly missing valuable spatial data in the sagittal and transversal plane such as the calcaneal shape [21]. Further translation of this method towards computer calculation of the inferior calcaneus point therefore can take place when using 3D segmented models, which are currently used for morphological characterization or joint configuration [22–24]. Another shortcoming can be attributed to the study population. Although the number is comparable to previous studies [17], the population was mostly taken from patients with persisting pain symptoms after sustaining a minor trauma such as an ankle distortion. Although not shown to be a primary risk factor [25], this population could have an intrinsic varus configuration and therefore be more prone in sustaining an ankle distortion. However, the obtained results are comparable to previous findings in healthy subjects [17], and the load-bearing area was found on the medial side of the calcaneus, which concurred with static podography study of Cavanagh et al. [26] Despite this concordance, it was pointed out recently by Richter et al. that a correlation between weight bearing CT images and podography was absent when using an incorporated pressure plate [27]. Further research can therefore analyze the influence of various types of hindfoot alignments on their bone distribution pattern using weight bearing CT compared to findings obtained from pressure plates both statically and dynamically [27]. In conclusion this paper shows a more neutral configuration of the hindfoot in the above population when using the HAIC based on the inferior point of the calcaneus. This method is supported by previous literature, a high reproducibility, and a load-bearing relevance as pointed out by the pixel bone density analysis [9, 17]. Future research should be aimed at translating the obtained measurement methods towards 3D segmented models to allow a higher accuracy. This will aid in preoperative planning and allow for a postoperative evaluation after multiplanar reconstructions. These findings should be combined with patient reported outcome measures (PROMs) and podographic and gait analysis to answer the question if the obtained neutral configuration should also be used in surgical hindfoot correction or fusion as compared to the proposed valgus position [12, 28].

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