

Clinical Research

Is Lower-limb Alignment Associated with Hindfoot Deformity in the Coronal Plane? A Weightbearing CT Analysis

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Abstract

Background The goals of lower limb reconstruction are to restore alignment, to improve function, and to reduce pain. However, it remains unclear whether alignment of the lower limb and hindfoot are associated because an accurate assessment of hindfoot deformities has been limited by superposition on plain radiography. Consequently, surgeons often overlook hindfoot deformity when planning orthopaedic procedures of the lower limb. Therefore, we used weight-bearing CT to quantify hindfoot deformity related to lower limb alignment in the coronal plane.

Questions/purposes (1) Is lower-limb alignment different in varus than in valgus hindfoot deformities for patients with and without tibiotalar joint osteoarthritis? (2) Does a

hindfoot deformity correlate with lower-limb alignment in patients with and without tibiotalar joint osteoarthritis? (3) Is joint line orientation different in varus than in valgus hindfoot deformities for patients with tibiotalar joint osteoarthritis? (4) Does a hindfoot deformity correlate with joint line orientation in patients with tibiotalar joint osteoarthritis?

Methods Between January 2015 and December 2017, one foot and ankle surgeon obtained weightbearing CT scans as second-line imaging for 184 patients with ankle and hindfoot disorders. In 69% (127 of 184 patients) of this cohort, a combined weightbearing CT and full-leg radiograph was performed when symptomatic hindfoot

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Each author certifies that his or her institution approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

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deformities were present. Of those, 85% (109 of 127 patients) with a median (range) age of 53 years (23 to 75) were confirmed eligible based on the inclusion and exclusion criteria of this retrospective comparative study. The Takakura classification was used to divide the cohort into patients with ($n = 74$) and without ($n = 35$) osteoarthritis of the tibiotalar joint. Lower-limb measurements, obtained from the full-leg radiographs, consisted of the mechanical tibiofemoral angle, mechanical tibia angle, and proximal tibial joint line angle. Weightbearing CT images were used to determine the hindfoot's alignment (mechanical hindfoot angle), the tibiotalar joint alignment (distal tibial joint line angle and talar tilt angle) and the subtalar joint alignment (subtalar vertical angle). These values were statistically assessed with an ANOVA and a pairwise comparison was subsequently performed with Tukey's adjustment. A linear regression analysis was performed using the Pearson correlation coefficient (r). A reliability analysis was performed using the intraclass correlation coefficient.

Results Lower limb alignment differed among patients with hindfoot deformity and among patients with or without tibiotalar joint osteoarthritis. In patients with tibiotalar joint osteoarthritis, we found knee valgus in presence of hindfoot varus deformity and knee varus in presence of hindfoot valgus deformity (mechanical tibiofemoral angle $0.3 \pm 2.6^\circ$ versus $-1.8 \pm 2.1^\circ$; $p < 0.001$; mechanical tibia angle $-1.4 \pm 2.2^\circ$ versus $-4.3 \pm 1.9^\circ$; $p < 0.001$). Patients without tibiotalar joint osteoarthritis demonstrated knee varus in the presence of hindfoot varus deformity compared with knee valgus in presence of hindfoot valgus deformity (mechanical tibiofemoral angle $-2.2 \pm 2.2^\circ$ versus $0.9 \pm 2.4^\circ$; $p < 0.001$; mechanical tibia angle $-1.8 \pm 2.1^\circ$ versus $-4.3 \pm 1.9^\circ$; $p < 0.001$). Patients with more valgus deformity in the hindfoot tended to have more tibiofemoral varus ($r = -0.38$) and tibial varus ($r = -0.53$), when tibiotalar joint osteoarthritis was present ($p < 0.001$). Conversely, patients with more valgus deformity in the hindfoot tended to have more tibiofemoral valgus ($r = 0.4$) and tibial valgus ($r = 0.46$), when tibiotalar joint osteoarthritis was absent ($p < 0.001$). The proximal joint line of the tibia had greater varus orientation in patients with a hindfoot valgus deformity compared with greater valgus orientation in patients with a hindfoot varus deformity (proximal tibial joint line angle $88.5 \pm 2.0^\circ$ versus $90.6 \pm 2.2^\circ$; $p < 0.05$). Patients with more valgus deformity in the hindfoot tended to have more varus angulation of the proximal tibial joint line angle ($r = 0.31$; $p < 0.05$).

Conclusions In patients with osteoarthritis of the tibiotalar joint, varus angulation of the knee was associated with hindfoot valgus deformity and valgus angulation of the knee was associated with hindfoot varus deformity. Patients without tibiotalar joint osteoarthritis exhibited the same deviation at the level of the knee and hindfoot. These distinct radiographic findings were most pronounced in the

alignment of the tibia relative to the hindfoot deformity. This suggests a detailed examination of hindfoot alignment before knee deformity correction at the level of the proximal tibia, to avoid postoperative increase of pre-existing hindfoot deformity. Other differences detected between the radiographic parameters were less pronounced and varied within the subgroups. Future research could identify prospectively which of these parameters contain clinical relevance by progressing osteoarthritis or deformity and how they can be altered by corrective treatment.

Level of Evidence Level III, prognostic study.

Introduction

The contribution of constitutional and acquired femoral and tibial deformities, especially of the hip and the knee, has been studied in detail [4, 35, 39, 41]. The mechanical tibiofemoral angle is commonly used to express this relationship and is considered a reference for evaluating overall lower-limb alignment in the coronal plane [12, 50]. The importance is reflected in the numerous joint-preserving and joint-replacing orthopaedic procedures that rely on this measurement [1, 22, 31, 35]. Despite its relevance, one crucial drawback of the mechanical tibiofemoral angle is its failure to account for hindfoot alignment because the caudal reference point of the mechanical tibial axis ends at the middle of the tibiotalar joint. Moreover, when hindfoot alignment is considered in clinical studies, a major change in the lower limb axis often occurs [16, 34, 52]. Computer-based studies have confirmed the influence of the hindfoot's position on lower-limb alignment in the coronal plane [15].

Lower limb osteoarthritis may affect axial alignment and joint line orientation, either directly or indirectly [4, 35, 39, 41]. In a cohort of patients with osteoarthritic knee deformities, Norton et al. [36] found valgus hindfoot orientation in a varus knee deformity and the opposite in a valgus knee deformity. This mechanism, presumably one of compensation, particularly occurs in the subtalar joint [47]. Correspondingly, in a cohort of patients with tibiotalar joint arthritis, the subtalar joint's orientation differed by up to 50% from the overall alignment of the hindfoot [57]. However, not every hindfoot with a deformity has this compensatory mechanism, and the exact occurrence rate is debatable [14, 25]. This may be partially attributed to difficulty in hindfoot imaging, which is limited by superposition and rotational errors encountered with plain radiographs [24]. The recent advent of weightbearing conebeam CT has allowed imaging of the foot and ankle at a lower radiation dose than conventional CT imaging [3, 32]. This technology accurately analyzes articular configurations and can account for rotational errors [13, 43]. Measurement techniques to assess hindfoot alignment and

joint line orientation on weightbearing conebeam CT images have been described, with a concomitant reliability analysis and reference values [6, 8, 11, 26]. However, the relationship between hindfoot deformity and lower-limb alignment in the coronal plane remains unclear.

In this study, we asked: (1) Is lower-limb alignment different in varus than in valgus hindfoot deformities for patients with and without tibiotalar joint osteoarthritis? (2) Does a hindfoot deformity correlate with lower-limb alignment in patients with and without tibiotalar joint osteoarthritis? (3) Is joint line orientation different in varus than in valgus hindfoot deformities for patients with tibiotalar joint osteoarthritis? (4) Does a hindfoot deformity correlate with joint line orientation in patients with tibiotalar joint osteoarthritis?

Patients and Methods

Study Design and Setting

Between January 2015 and December 2017, one foot and ankle surgeon (KB) requested a weightbearing CT scan of 184 patients as second-line imaging. Of those, 69% (127 of 184 patients) had a combined full-leg radiograph and weightbearing conebeam CT examination. In general, we ordered both tests in patients with persistent signs and symptoms of hindfoot varus and valgus deformities despite previous conservative or surgical treatment. Heel inversion with peroneal tendon/lateral ankle ligament tenderness was considered for hindfoot varus deformities and heel eversion with tibial posterior tendon/deltoid ligament for hindfoot valgus deformities. Of those, 85% (109 out of 127 patients) were included in this retrospective comparative study (Fig. 1).

Participants

The study population consisted of 57 male and 52 female patients with a median (range) age of 54 years (23 to 75) (Table 1). The inclusion criteria were patients between 18 and 75 years old with hindfoot deformity imaged by both a full-leg radiograph and weightbearing conebeam CT. The exclusion criteria were congenital disorders affecting lower-limb alignment such as cerebral palsy, rickets, and achondroplasia; absence of or an incomplete full-leg radiograph and weightbearing conebeam CT images; previous hindfoot surgery or knee realignment; posttraumatic deformities above the distal third of the tibia; TKA; or a leg-length discrepancy of more than 3 cm. Patients' records and radiographs were reviewed by two orthopaedic surgeons (KB, a foot and ankle surgeon with 20 years of experience, and ABMB, an orthopaedic resident with 6 years of

experience). Our institutional review board approved this study, and the need to obtain informed consent was waived.

Variables, Outcome Measures, Data Sources, and Bias

Weightbearing full-leg radiographs were obtained with patients standing barefoot with both feet together and the patella facing forward as described by Paley et al. [41], using an Ysio[®] digital radiography system (Siemens, Erlangen, Germany) at 85 kV and a focus-to-detector distance of 3 meters. Measurements were performed using OsiriX[®] v1.6.2 software (Osirix, Geneva, Switzerland) [45].

Weightbearing CT images were obtained with a PedCAT[®] device (Curvebeam, Warrington, PA, USA) and patients were positioned according to the same protocol as for the full-leg radiographs. The following imaging protocol and settings were used for weightbearing conebeam CT: tube voltage: 96 kV; tube current: 7.5 mAs; CTDIvol: 4.3 mGy; matrix: 160 x 160 x 130; pixel size: 0.4 mm; and slice interval: 0.4 mm.

The axial radiographic alignment is noted as a deviation from 180°; positive values represent valgus alignment and negative values represent varus alignment.

The joint line's orientation is referenced toward the vertical axis perpendicular to the floor and noted as at least 90° (valgus alignment) or less than 90° (varus alignment) (Fig. 2A).

Three angles were determined on each full-leg radiograph in the coronal plane by two authors (ABMB, EV): the mechanical tibiofemoral angle, mechanical tibia angle, and the proximal tibial joint line angle. The mechanical tibiofemoral angle was used to assess the lower limb's alignment and was defined by the intersection of the mechanical femur axis and mechanical tibia axis [12]. The mechanical femur axis was obtained by connecting the center of the femoral head, determined by a concentric digital template, with the apex of the femoral notch (Fig. 2A) [12, 33]. The mechanical tibia axis was obtained by connecting the midpoint between the tip of the medial and lateral intercondylar tubercles with the midpoint between the tibia and fibula at the plafond [23]. The mechanical tibia angle was determined by the intersection of the mechanical tibia axis and the vertical axis. The mechanical tibia angle was assessed separately from the mechanical tibiofemoral angle because hindfoot alignment is often referenced toward the tibia [12, 33]. The proximal tibia joint line axis was determined by the line tangential to the medial and lateral tibial plateau and was intersected with the vertical axis to obtain the concomitant proximal tibia joint line angle (Fig. 2A) [56].

Two authors (ABMB, PD) determined the following radiographic parameters on weightbearing conebeam CT images in the coronal plane: the hindfoot alignment

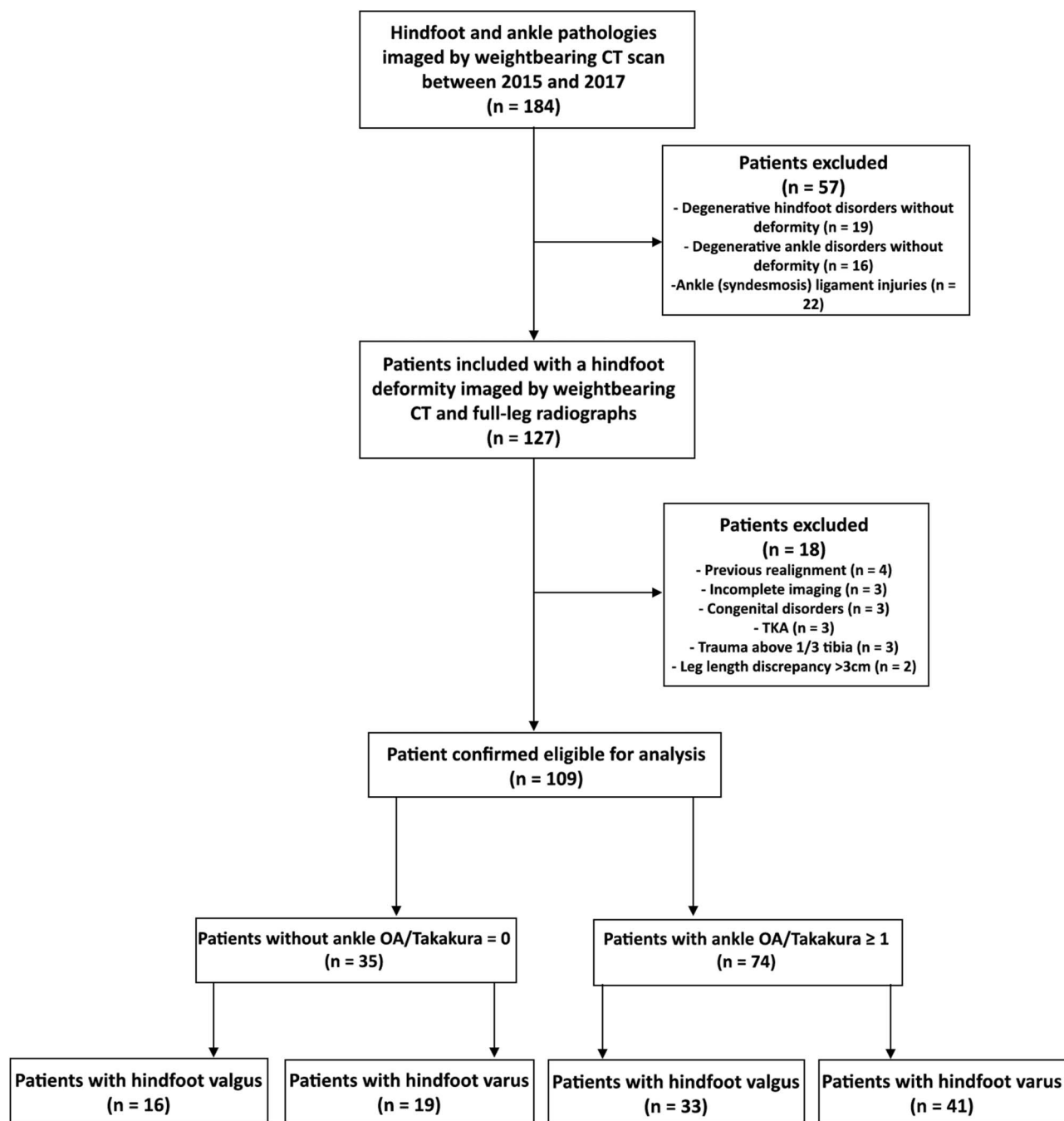


Fig. 1 This flowchart shows the study enrollment process.

containing the mechanical hindfoot axis; the tibiotalar joint alignment, consisting of the distal tibial joint line axis and talar tilt axis; and the subtalar joint alignment, defined by the subtalar vertical axis [6, 8, 19, 43]. All axes were measured toward the vertical axis to obtain the concomitant angle. We used the multiplanar reconstruction mode to allow simultaneous assessment of orthogonal CT-slices in the coronal, axial, and sagittal planes. This post-imaging

process accounted for rotational errors in patient positioning, by aligning each foot along the longitudinal axis of the second metatarsal in the axial plane, commonly used as a reference position [2, 11, 26].

On combined CT slices, digitally reconstructed AP ankle radiographs were generated by the weightbearing conebeam CT software [8, 29]. We used the corresponding reconstructed radiograph in the coronal plane to define the

Table 1. Baseline demographic and radiographic information

Parameter	Takakura = 0		Takakura ≥ 1	
	Valgus	Varus	Valgus	Varus
Number of patients	16	19	33	41
Age (years, range)	50 (23-69)	47 (24-67)	59 (25-75)	53 (27-75)
Gender M/F (%)	7/9 (43/57)	12/7 (63/37)	13/20 (39/61)	25/16 (60/40)
Takakura stage of ankle osteoarthritis (%)				
Stage 0 (absence osteoarthritis)	16 (100)	19 (100)		
Stage 1			6 (18)	11 (25)
Stage 2			17 (51)	21 (48)
Stage 3a			5 (15)	6 (14)
Stage 3b			3 (9)	2 (5)
Stage 4			2 (6)	1 (2)
Kellgren-Lawrence stage of ankle osteoarthritis (%)				
Stage 0 (absence of osteoarthritis)	10 (63)	9 (47)	9 (27)	12 (29)
Stages 1-2 (minor osteoarthritis)	6 (37)	9 (47)	20 (60)	24 (60)
Stages 3-4 (major osteoarthritis)		1 (6)	4 (13)	5 (12)

mechanical hindfoot axis by connecting the most inferior point of the calcaneus with the midpoint of the superior facet of the talus (reported normal value: $0.61 \pm 2.9^\circ$ of valgus) (Fig. 2B) [6, 8].

On single CT slices, we determined the most superior point of the talar dome in the sagittal plane using the multiplanar reconstruction mode. The corresponding CT image in the coronal plane was used to define the distal tibial joint line axis, as the axis parallel to the distal joint surface of the tibia, and the talar tilt axis, as the axis parallel to the superior facet of the talus (reported normal value of the distal tibial joint line angle: $88.1 \pm 3.1^\circ$ of varus; talar tilt angle: $87.6 \pm 3.9^\circ$ of varus) (Fig. 2C) [6].

Further on single CT slices, we determined the midpoint of the posterior subtalar joint's facet in the sagittal plane using the multiplanar reconstruction mode. We used the corresponding CT image in the coronal plane to define the subtalar vertical axis as the axis parallel to the posterior subtalar joint's facet (reported normal value of the subtalar vertical angle: 98° of valgus (range 85 to 114) (Fig. 2D) [11].

Accounting for All Patients

We used the Takakura classification system to determine the degree of tibiotalar joint osteoarthritis on digitally reconstructed AP ankle radiographs [17]. The cohort was divided into patients without radiographic signs of tibiotalar joint osteoarthritis (Takakura stage 0; $n = 35$) and patients with radiographic signs of tibiotalar joint osteoarthritis (Takakura stage 1 or above; $n = 74$) containing

different etiologies (Table 2). The median (range) age of patients without tibiotalar joint osteoarthritis was 48 years (23 to 64) and the mean (range) age of patients with tibiotalar joint osteoarthritis was 57 years (27 to 75). Patients in the hindfoot valgus group were subdivided according to whether the mechanical hindfoot angle was positive, and patients in the hindfoot varus group were subdivided according to whether the mechanical hindfoot angle was negative (Fig. 1). These groups were used to perform the proposed comparisons and correlation analysis using the aforementioned radiographic measurements.

We assessed knee osteoarthritis using the Kellgren-Lawrence classification system [23]. To account for correlated data in the study population, we included only one lower limb from each patient in the analysis [46, 50]. The right limb was selected for patients with a bilateral hindfoot deformity with or without tibiotalar joint osteoarthritis. The concomitant limb of the affected side was selected in patients with a unilateral hindfoot deformity with or without tibiotalar joint osteoarthritis.

Statistical Analysis, Study Size

A Kolmogorov-Smirnov normality test was conducted for each radiographic outcome and demonstrated a p value greater than 0.05, indicating normal distribution of the data and the need for further parametric testing. Comparison of the angular outcomes among the four groups was performed using a one-way ANOVA. When the global F -test result of the ANOVA was statistically significant, a further

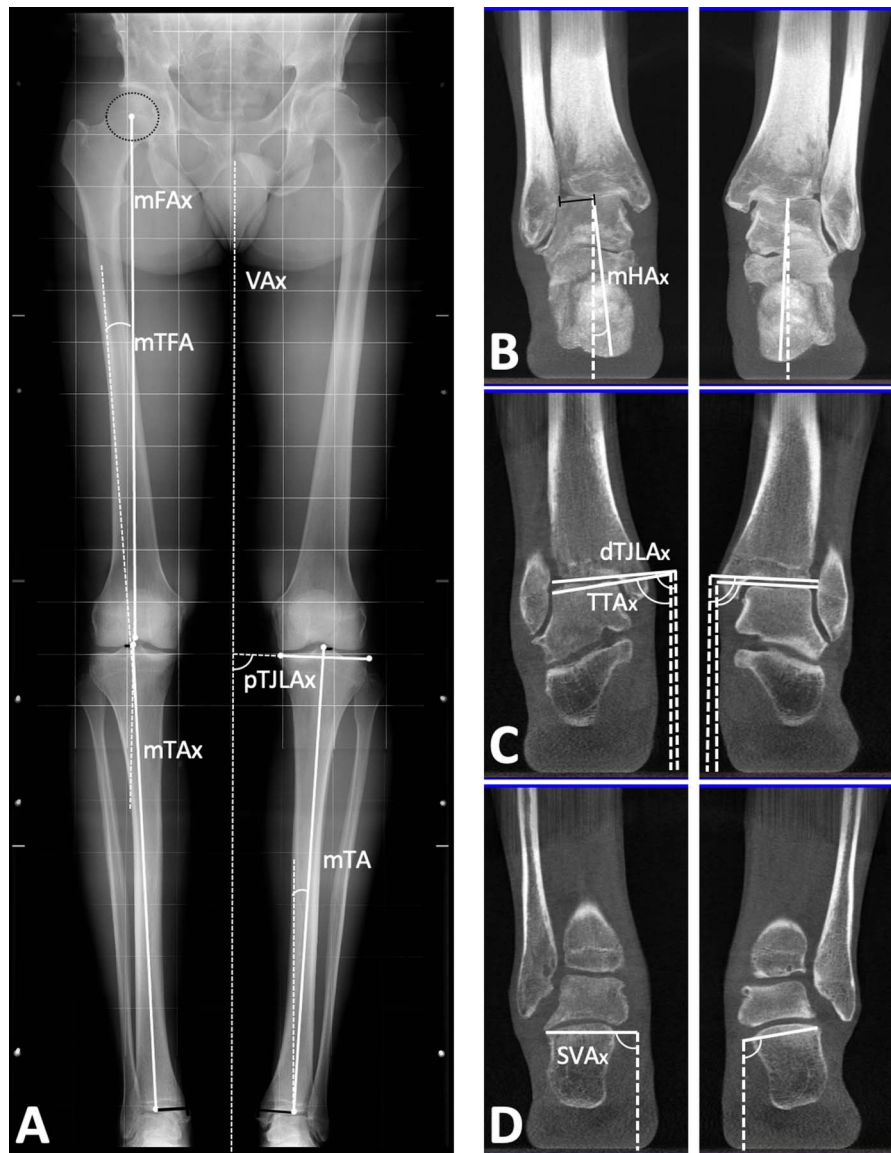


Fig. 2A-D Measurements were made on full-leg radiographs and weightbearing CT images. **(A)** The mechanical tibiofemoral angle (mTFA) was demonstrated on the right limb and obtained by the intersection of the mechanical femoral axis (mFAx) and mechanical tibia axis (mTAx). The mechanical tibia angle (mTA) and proximal tibial joint line angle (pTJLA) are depicted on the left limb and were determined by the intersection of their concomitant axes and the vertical axis (VAx) connecting the center of the pubic symphysis perpendicular to the floor. **(B)** The mechanical hindfoot angle (mHA) was determined by the intersection between the vertical axis and the mechanical hindfoot axis (mHAx) connecting the midpoint of the superior talar facet with the inferior point of the calcaneus. **(C)** The subtalar vertical angle (SVA) was determined as the intersection between the vertical axis and the subtalar vertical axis (SVAx), parallel to the posterior facet of the subtalar joint. **(D)** The distal tibial joint line angle (dTJLA) was defined as the intersection between the vertical axis and the axis parallel to the distal joint surface of the tibia, and the talar tilt angle (TTA) was defined as the intersection between the vertical axis and the talar tilt axis (TTAx) parallel to the superior facet of the talus.

analysis was undertaken by performing pairwise comparisons. This was conducted using the Tukey-Kramer post-hoc test to control for the overall Type I error rate and the

unequal sample size among the different groups. The correlation between the full-leg radiographic and weightbearing CT hindfoot measurements was assessed with the

Table 2. Etiology of hindfoot deformities

Etiology (number, %)	Takakura = 0		Takakura ≥ 1	
	Valgus	Varus	Valgus	Varus
Idiopathic				7 (17)
Post-traumatic			7 (21)	21 (51)
AAFD				
Stage I	5 (32)			
Stage II				
Stage III			12 (36)	
Stage IV			6 (18)	
Constitutional		15 (78)		
Avascular necrosis			1 (3)	3 (8)
Septic			1 (3)	2 (5)
Neurologic		4 (22)		5 (12)
Hemophilia			1 (3)	2 (5)
Rheumatoid			5 (16)	1 (2)

AAFD = adult acquired flat foot deformity.

Pearson coefficient (r). A linear regression analysis was performed using a corresponding scatter plot. The interobserver and intraobserver observer variability were determined using the interclass correlation coefficient (ICC) at 1-month intervals in 23 patients (20% of the study population) who were randomly selected by the statistical software in accordance with the method of a previous study [26]. Interpretations were as follows: ICC < 0.4: poor; ICC 0.4 to 0.59: acceptable; ICC 0.6 to 0.74: good; and ICC > 0.74, excellent [51]. The SPSS statistical package (version 25.0.0. standard version, SPSS Inc, Chicago, IL, USA) was used to analyze the results. A p value < 0.05 was considered significant. A statistical power analysis using the SAS® Power and Sample Size application (SAS Inc, Cary, NC, USA) was performed to estimate the sample size, based on previously reported data regarding the primary parameter associated with alignment of the lower limb: mechanical tibiofemoral angle [44]. A minimal sample size of 12 patients needed to be enrolled in each subgroup to reach the calculated effect size (f = 1.8), with a power level of 0.8 and level of significance of 0.05.

Results

Is Lower-limb Alignment Different in Varus Than in Valgus Hindfoot Deformities for Patients With and Without Tibiotalar Joint Osteoarthritis?

Lower limb alignment differed among patients with hindfoot deformity and among patients with or without tibiotalar joint osteoarthritis. In patients with tibiotalar joint osteoarthritis we found knee valgus (Fig. 3A) in presence

of hindfoot varus deformity and knee varus (Fig. 3B) in presence of hindfoot valgus deformity (mechanical tibiofemoral angle $0.3 \pm 2.6^\circ$ versus $-1.8 \pm 2.1^\circ$; mechanical tibia angle $-1.4 \pm 2.2^\circ$ versus $-4.3 \pm 1.9^\circ$) (Table 3; p < 0.001). Patients without tibiotalar joint osteoarthritis demonstrated knee varus (Fig. 4A) in the presence of hindfoot varus deformity compared with knee valgus (Fig. 4B) in the presence of hindfoot valgus deformity (mechanical tibiofemoral angle $-2.2 \pm 2.2^\circ$ versus $0.9 \pm 2.4^\circ$; mechanical tibia angle $-4.3 \pm 1.9^\circ$ versus $-1.8 \pm 2.1^\circ$) (Table 3; p < 0.001).

Does a Hindfoot Deformity Correlate With Lower-limb Alignment in Patients With and Without Tibiotalar Joint Osteoarthritis?

Patients with more valgus deformity in the hindfoot tended to have more tibial varus (r = -0.53; p < 0.001; Fig. 5A) and tibiofemoral varus (r = -0.38; p < 0.001; Fig. 5B), when tibiotalar joint osteoarthritis was present. Conversely, patients with more valgus deformity in the hindfoot tended to have more tibial valgus (r = 0.46; p < 0.001; Fig. 5C) and tibiofemoral valgus (r = 0.4; p < 0.001; Fig. 5D), when tibiotalar joint osteoarthritis was absent.

Is the Tibial Joint Line’s Orientation Different in Varus than in Valgus Hindfoot Deformities for Patients with Tibiotalar Joint Osteoarthritis?

The joint line orientation at both ends of the tibia demonstrated greater varus angulation in patients with

hindfoot valgus deformity and differed from greater valgus angulation at both ends of the tibia in patients with hindfoot varus deformity (proximal tibial joint line angle $88.5 \pm 2.0^\circ$ versus $90.6 \pm 2.2^\circ$ and distal tibial joint line angle $86.7 \pm 0.5^\circ$ versus $91.4 \pm 0.4^\circ$) ($p < 0.05$; Table 4). The joint line orientation of hindfoot deformities demonstrated greater valgus orientation of the superior facet of the talus and posterior facet of the subtalar joint in patients with hindfoot valgus, which differed from greater varus orientation in patients with hindfoot varus (talar tilt angle $91.2^\circ \pm 3.9^\circ$ versus $87.6^\circ \pm 4.5^\circ$; subtalar vertical angle $106.9^\circ \pm 8.0^\circ$ versus $89.3^\circ \pm 13.9^\circ$) ($p < 0.001$; Table 4).

Does a Hindfoot Deformity Correlate with the Tibial Joint Line's Orientation in Patients with Tibiotalar Joint Osteoarthritis?

Patients with more valgus deformity in the hindfoot tended to have more varus angulation of the proximal tibial joint line ($r = -0.31$; $p < 0.05$; Fig. 6A) and distal tibial joint line ($r = -0.51$; $p < 0.001$; Fig. 6B).

Other Relevant Findings

The mean Kellgren-Lawrence score was 0.57 ± 0.7 in the group of patients without tibiotalar joint osteoarthritis. This was lower than the mean Kellgren-Lawrence score of 1.26 ± 0.9 in patients with tibiotalar joint osteoarthritis (95% CI -0.99 to -0.38 ; $p < 0.001$). The intraclass correlation coefficients (ICCs) for both groups were excellent. The ICCs of the lower limb and hindfoot measurements in the group of patients without tibiotalar joint osteoarthritis (range 0.892 to 0.978) were higher than those in the group of patients with tibiotalar joint osteoarthritis (range 0.834 to 0.928) (Table 5).

Discussion

The relation between osteoarthritic knee deformities and their hindfoot alignment has been demonstrated previously [36]. However, the opposite relationship, between hindfoot deformities and lower-limb alignment, has not been investigated. Moreover, an accurate analysis of axial alignment and orientation of the joint line using plain radiographs

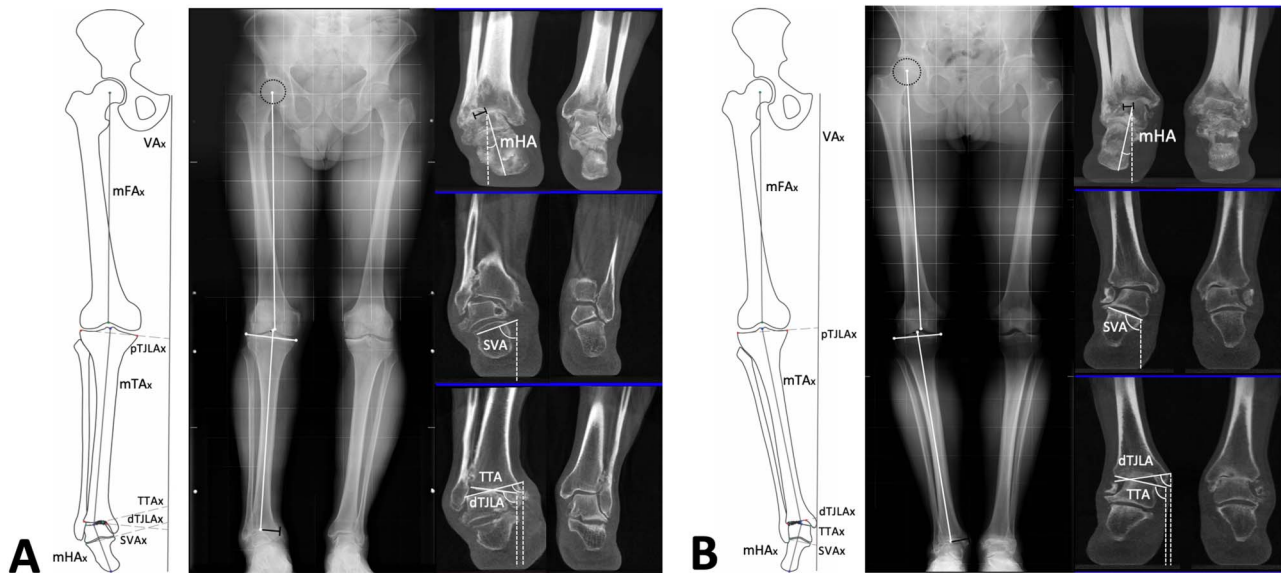


Fig. 3A-B Full-leg radiographs and weightbearing CT measurements were taken in patients with tibiotalar joint osteoarthritis. **(A)** Axial alignment of the right hindfoot was measured with the mechanical hindfoot angle (mHA) and demonstrated that a varus deformity was present. The associated joint lines of the hindfoot, measured with the talar tilt angle (TTA) at the superior facet of the talus and the subtalar vertical angle (SVA) at the posterior facet of the subtalar joint, are orientated in varus. The mechanical tibia angle (mTA), proximal tibial joint line angle (pTJLA), and distal tibial joint line angle were orientated in valgus, and were associated with opposing angulation toward axial alignment and orientation of the joint line in patients with a hindfoot deformity. **(B)** The opposite pattern is demonstrated in a patient with a valgus deformity of the right hindfoot; the axial alignment (mechanical hindfoot angle) and orientation of the joint lines (talar tilt angle and subtalar vertical angle) demonstrated that valgus alignment was present. The axial alignment of the tibia (mechanical tibia angle) and orientation of the proximal and distal joint line of the tibia (proximal and distal tibial joint line angle) demonstrated presence of a varus alignment and were associated with opposing angulation towards the hindfoot deformity.

Table 3. ANOVA of radiographic lower limb alignment measurements of a valgus and varus hindfoot in patients with and without tibiotalar joint osteoarthritis

Radiographic measurement	Group	Mean	SD	Range	Pairwise comparisons ^a
Mechanical tibiofemoral angle	Takakura = 0 valgus	0.9	2.41	-5.3 to 10.3	Takakura = 0 valgus vs Takakura = 0 varus (mean difference 8.4 [95% CI 1.6-15.2]; p = 0.008)
	Takakura = 0 varus	-2.2	2.2	-6.7 to 1.7	
	Takakura ≥ 1 valgus	-1.8	2.1	-6.32 to 3.27	Takakura ≥ 1 valgus vs Takakura ≥ 1 varus (mean difference -2.0 [95% CI -3.01 to -1.01]; p < 0.001)
	Takakura ≥ 1 varus	0.3	2.6	-7.08 to 4.9	
Mechanical tibia angle	Takakura = 0 valgus	-1.8	1.9	-4.9 to 1.6	Takakura = 0 valgus vs Takakura = 0 varus (mean difference 2.4 [95% CI 0.8-4.0]; p = 0.001)
	Takakura = 0 varus	-4.3	1.9	-8.0 to 0.1	
	Takakura ≥ 1 valgus	-4.0	2.1	-8.5 to 1.1	Takakura ≥ 1 valgus vs Takakura ≥ 1 varus (mean difference -2.6 [95% CI -3.7 to -1.4]; p < 0.001)
	Takakura ≥ 1 varus	-1.4	2.2	-5.6 to 4.4	
Proximal tibial joint line angle	Takakura = 0 valgus	89.2	2.31	85.9 to 94.2	Takakura = 0 valgus vs Takakura = 0 varus (mean difference 0.4 [95% CI -1.5 to 2.2]; p = 0.95)
	Takakura = 0 varus	88.8	2.9	84.5 to 93.0	
	Takakura ≥ 1 valgus	88.5	2.0	84.0 to 93.0	Takakura ≥ 1 valgus vs Takakura ≥ 1 varus (mean difference -1.6 [95% CI -2.9 to -0.3]; p = 0.01)
	Takakura ≥ 1 varus	90.6	2.2	85.0 to 97.9	

^aIndividual pairwise comparison with difference of means, 95% CI for difference in means, and p values based on the Tukey-Kramer method to correct for multiple comparisons and unequal sample size in the different groups.

is limited by superposition encountered on plain radiographs. Weightbearing conebeam CT was used to overcome this restriction and enable a detailed evaluation of the hindfoot's alignment. We found an association in patients with tibiotalar joint osteoarthritis between varus alignment of the knee in those with a hindfoot valgus deformity and with valgus alignment of the knee in those with a hindfoot varus deformity. Lower limb alignment in patients without tibiotalar joint osteoarthritis was associated with similar deviations at the level of the knee and hindfoot.

Several limitations were encountered during the study. First, we used a control group of patients who did not have tibiotalar joint osteoarthritis, but we did not control for hindfoot deformities. However, using a control group sampled from the general population, with absence of tibiotalar joint osteoarthritis and a hindfoot deformity would require both full-leg radiographic and weight-bearing CT imaging, resulting in a level of radiation exposure that would be difficult to justify. To resolve this issue, we used reference values from previous studies for comparison [8, 9, 26, 56]. Second, the results were limited to one measurement of each radiographic parameter in the coronal plane, omitting sagittal deformities and axial rotations. In addition, radiographic analysis was limited to 2-D measurements of anatomical structures or deformities, which are 3-D in nature [20, 21, 47]. To overcome this shortcoming, other imaging modalities that generate

3-D models can be used, either ranging from the ankle to the pelvis or from the foot to the distal femur [42, 53]. However, debate remains on the exact methodology of translating established radiographic 2-D measurements to computed 3-D angles [5, 7, 30]. Third, the study design is retrospective, and important clinical data such as the ligament conditions (stiffness or laxity), ROM (assessed in the knee, ankle, as well as hindfoot- and midfoot joints) and the exact occurrence of a hindfoot deformity in relation to knee malalignment were not typically reported or available. However, the aim of this study was to evaluate the radiographic association at presentation to a clinical practice. Nevertheless, prospective research should assess if patients with ligament laxity or stiffness impose different types of deformities or other compensatory mechanisms [27]. Fourth, the classification of hindfoot varus and valgus alignment was based on a narrow range, potentially resulting in a misclassification of the hindfoot deformity. However, rater reliability was high, and all patients were considered during the correlation analysis, regardless of whether they had a varus or valgus deformity. Similarly, the division in tibiotalar joint osteoarthritis was based on one stage difference and no further subgroup analysis could be performed based on the sample size calculation. This can be addressed in future research by increasing patient cohort size to allow stratification according to the degree of ankle or knee osteoarthritis.

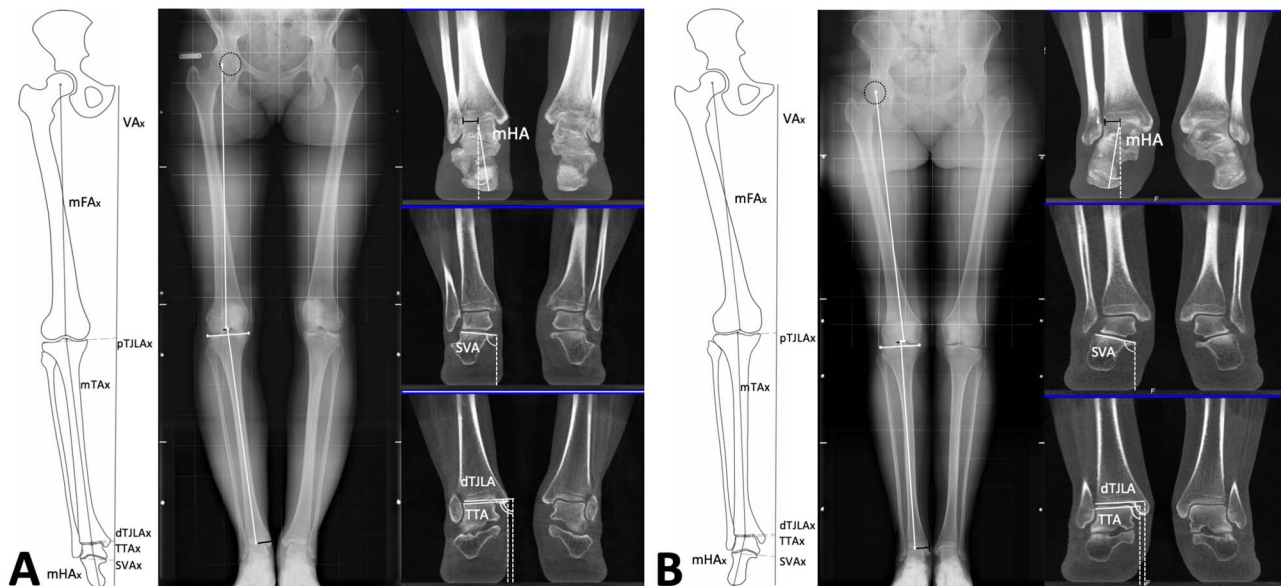


Fig. 4A-B Full-leg radiographs and weightbearing CT measurements were taken in patients without tibiotalar joint osteoarthritis. **(A)** Varus alignment of the hindfoot is demonstrated by the mechanical hindfoot angle (mHA) and was associated with varus alignment of the lower limb by the mechanical tibiofemoral angle (mTFA) **(B)** Conversely, valgus alignment of the hindfoot was associated with valgus alignment of the lower limb.

Is Lower-limb Alignment Different in Varus Than in Valgus Hindfoot Deformities for Patients With and Without Tibiotalar Joint Osteoarthritis?

We found that axial lower limb alignment differed between varus and valgus hindfoot deformities, and that the direction of the deformity differed depending on whether tibiotalar osteoarthritis was present. Thus, clinicians cannot assume from short knee radiographs that the hindfoot will be aligned in the same direction as the knee. In the setting of planned knee deformity correction at the level of the tibia by either knee arthroplasty or osteotomy, pre-existing osteoarthritic hindfoot deformities are important to detect as they are known to adversely affect clinical and radiographic outcome [10, 49]. In a previous study comparing hindfoot alignment in patients with osteoarthritic knee deformities, a varus knee deformity was associated with a hindfoot valgus angle and a valgus knee deformity was associated with a hindfoot varus angle [36]. However, that study's cohort consisted of patients with end-stage knee arthritis, in contrast to the current study population, who had a mean Kellgren-Lawrence knee osteoarthritis score of 1.6. In addition, almost half of their cohort presented with a knee deformity of greater than 10°, which differed from the current study's population, which consisted of only one patient with a knee deformity greater than 10°. In the current study, the radiographic differences were often small with a considerable variation within the subgroups.

The difference in the mechanical tibiofemoral angle between hindfoot varus and valgus deformities in patients with osteoarthritis was 2.1°, which is of questionable clinical relevance. However, mechanical tibia angles in these patient groups differed by 3.4°, which is clinically relevant [28]. This discrepancy could be a consequence of differences in femoral alignment, which ranges from 4° to 12° of valgus and is unrelated to tibial alignment [19]. Other reasons for this variation can be attributed to the inhomogeneous distribution of patients with tibiotalar joint osteoarthritis according to the Takakura classification and differences in etiology of hindfoot deformities, as post-traumatic deformities present a distinct pathoanatomy compared with neurological or systemic etiologies [55]. This may alter findings in other patients groups and can be controlled in future studies by stratifying the hindfoot deformities according to sample size and etiology.

Does a Hindfoot Deformity Correlate With Axial Lower-limb Alignment in for Patients With and Without Tibiotalar Joint Osteoarthritis?

We detected different relationships between axial lower-limb alignment and hindfoot deformity, depending on the presence or absence of tibiotalar osteoarthritis. The hindfoot alignment in patients with tibiotalar joint osteoarthritis demonstrated more varus, while the lower

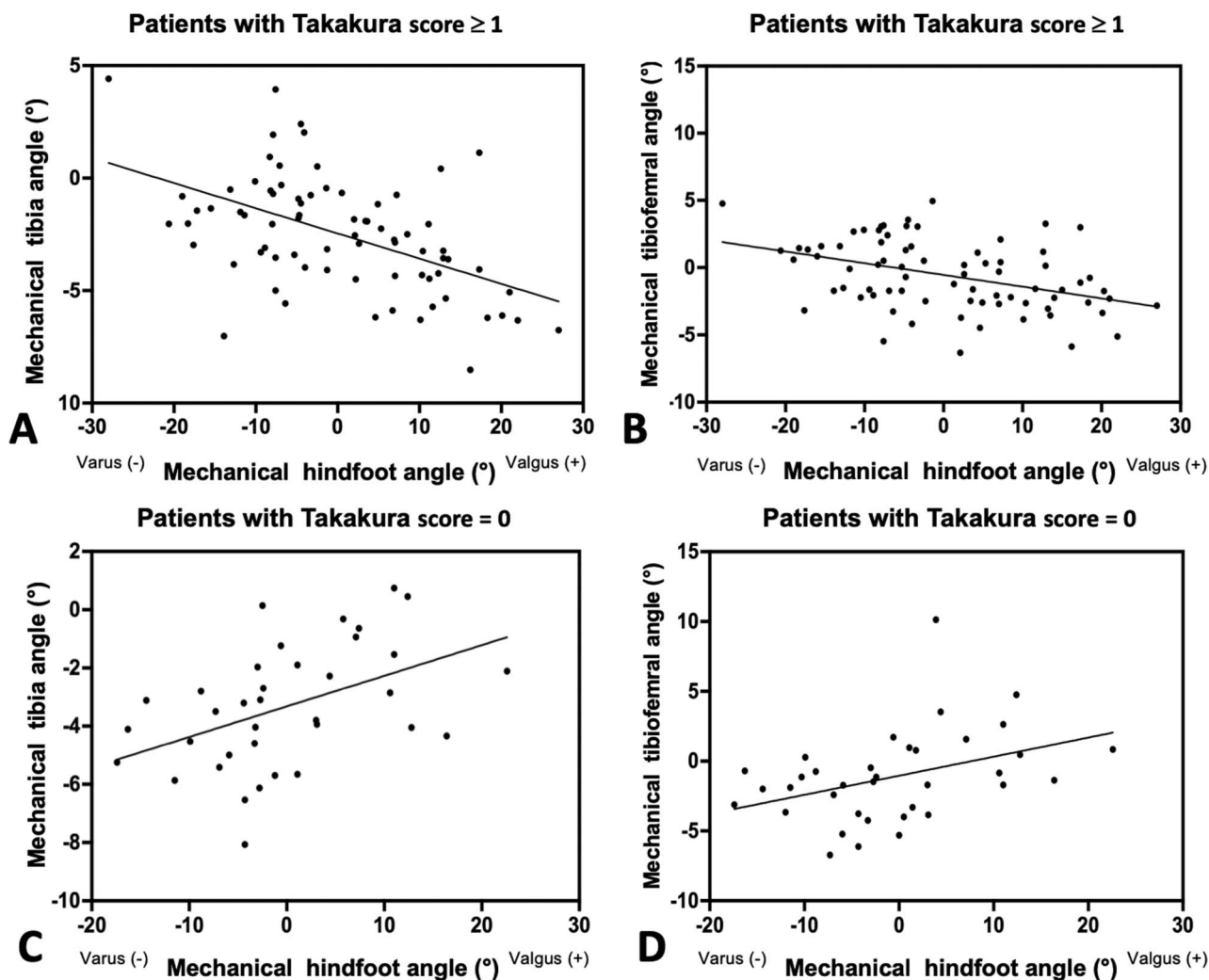


Fig. 5A-D A linear regression analysis was performed between the mechanical hindfoot angle and both the mechanical tibia angle and mechanical tibiofemoral angle. These images show (A) the correlation between the mechanical tibia angle and hindfoot alignment in patients with tibiotalar joint osteoarthritis ($r = -0.46$, $y = 0.12$, $x - 3.2$; $p < 0.001$), (B) the correlation between the mechanical tibiofemoral angle and hindfoot alignment in patients with tibiotalar joint osteoarthritis ($r = -0.4$, $y = 0.14$, $x - 1.0$; $p < 0.001$), (C) the correlation between the mechanical tibia angle and hindfoot alignment in patients without tibiotalar joint osteoarthritis ($r = 0.53$, $y = -0.12$, $x - 2.5$; $p < 0.001$), and (D) the correlation between the mechanical tibiofemoral angle and hindfoot alignment in patients without tibiotalar joint osteoarthritis ($r = 0.38$, $y = -0.09$, $x - 0.6$; $p < 0.001$).

limb alignment contained more valgus. This contradicts the previous assumption that hindfoot valgus is associated with valgus alignment of the lower limb and vice versa [38]. However, similar to the result of a previous study, we demonstrated a linear increase of the hindfoot angle in relation to increasing axial lower limb angles in patients without tibiotalar joint osteoarthritis [44]. This distinct relationship between patients with and without arthritis is currently not well understood, but it could be attributed to changes in bone morphology and soft-tissue laxity occurring in patients with osteoarthritis [18, 37, 54]. These changes may alter axial alignment and joint line orientation [54].

Is the Tibial Joint Line’s Orientation Different in Varus than in Valgus Hindfoot Deformities for Patients with Tibiotalar Joint Osteoarthritis?

We found that the orientation of the tibial joint line in the knee and ankle differed between varus and valgus hindfoot deformities with tibiotalar joint osteoarthritis. Tibial alignment was associated with opposing angulation of the mechanical axis and joint line orientation towards a hindfoot varus or valgus deformity. This has not been found on full-leg radiographs, but it could be detected on Mortise ankle images in patients who underwent realignment procedures for hindfoot varus and valgus

Table 4. ANOVA of radiographic hindfoot alignment measurements of valgus and varus hindfoot deformities in patients with and without tibiotalar joint osteoarthritis

Radiographic measurement	Group	Mean	SD	Range	Pairwise comparisons ^a
Mechanical hindfoot axis	Takakura = 0 valgus	6.9	5.3	0-19.6	Takakura = 0 valgus vs Takakura = 0 varus (mean difference 12.7 [95% CI 8.5 to 16.9]; $p < 0.001$)
	Takakura = 0 varus	-5.8	4.6	-16.4 to -0.5	
	Takakura ≥ 1 valgus	11.2	5.9	3.1-27.0	Takakura ≥ 1 valgus vs Takakura ≥ 1 varus (mean difference 20.8 [95% CI 17.9 to 23.7]; $p < 0.001$)
	Takakura ≥ 1 varus	-9.6	5.0	-28 to -4.3	
Subtalar vertical angle	Takakura = 0 valgus	101.3	7.3	87.6 to 117.0	Takakura = 0 valgus vs Takakura = 0 varus (mean difference 7.5 [95% CI -0.81 to 15.7]; $p = 0.093$)
	Takakura = 0 varus	93.8	5.8	80.6 to 103.0	
	Takakura ≥ 1 valgus	106.9	8.0	85.7 to 123.3	Takakura ≥ 1 valgus vs Takakura ≥ 1 varus (mean difference 16.3 [95% CI 9.6 to 17.5]; $p < 0.001$)
	Takakura ≥ 1 varus	89.3	13.9	67 to 110.3	
Talar tilt angle	Takakura = 0 valgus	87.6	3.1	80.1 to 91.7	Takakura = 0 valgus vs Takakura = 0 varus (mean difference -1.2 [95% CI -4.2 to 1.9]; $p = 0.753$)
	Takakura = 0 varus	88.8	2.4	81.3 to 92.9	
	Takakura ≥ 1 valgus	91.2	3.9	82.7 to 99.5	Takakura ≥ 1 valgus vs Takakura ≥ 1 varus (mean difference 2.4 [95% CI 0.3 to 4.5]; $p = 0.016$)
	Takakura ≥ 1 varus	87.6	4.5	79.0 to 99.6	
Distal tibial joint line angle	Takakura = 0 valgus	86.7	0.7	82.3 to 93.4	Takakura = 0 valgus vs Takakura = 0 varus (mean difference 0.4 [95% CI -1.9 to 2.7]; $p = 0.98$)
	Takakura = 0 varus	87.9	0.5	80.8 to 94.4	
	Takakura ≥ 1 valgus	86.7	0.5	79.6 to 92.7	Takakura ≥ 1 valgus vs Takakura ≥ 1 varus (mean difference -2.1 [95% CI -4.2 to -0.93]; $p = 0.026$)
	Takakura ≥ 1 varus	91.4	0.4	83.2 to 99.7	

^aIndividual pairwise comparison with difference of means, 95% CI for difference in means, and p values based on the Tukey-Kramer method to correct for multiple comparisons and unequal sample size in the different groups.

deformities [40]. Opposing alignment between the hindfoot deformity and lower-limb alignment may have bio-mechanical benefits by reducing the amount of knee

deviation towards the ground mechanical axis (connecting the center of the hip to the ground by including the inferior part of the calcaneus) [54].

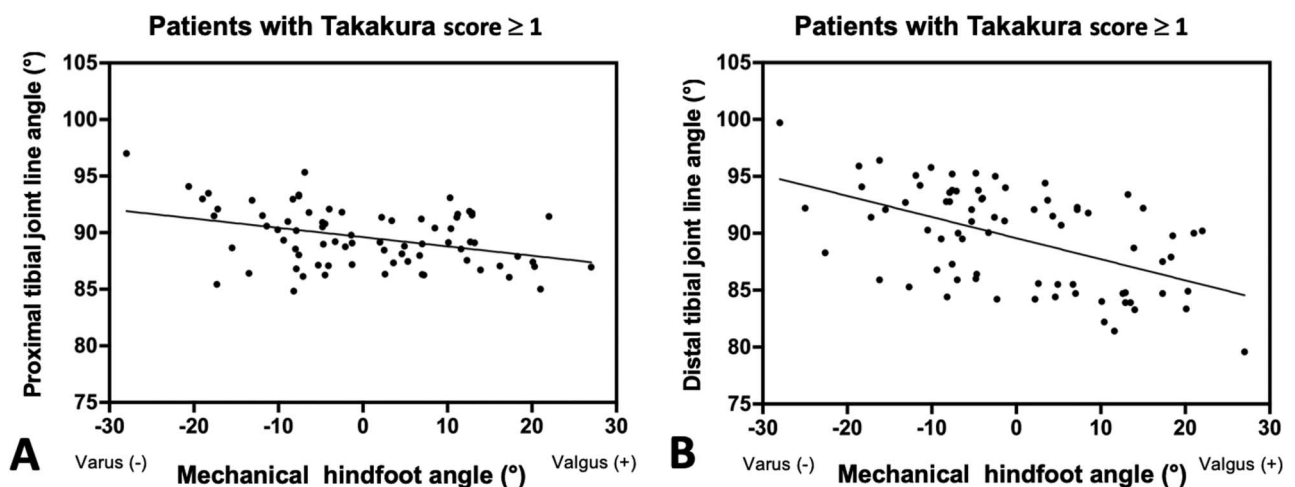


Fig. 6A-B A linear regression analysis was performed between the mechanical hindfoot angle and both the proximal and distal tibial joint line angle. These images show (A) the correlation between the mechanical tibia angle and hindfoot alignment in patients with tibiotalar joint osteoarthritis ($r = -0.31$, $y = -0.08x + 89.6$; $p < 0.05$), (B) the correlation between the mechanical tibiofemoral angle and hindfoot alignment in patients with tibiotalar joint osteoarthritis ($r = -0.51$, $y = -0.19x + 89.6$; $p < 0.001$).

Table 5. Interobserver and intraobserver reliability for measurement of alignment of the hindfoot and lower limb

Radiographic measurement	ICCs Takakura = 0		ICCs Takakura ≥ 1	
	Interobserver	Intraobserver	Interobserver	Intraobserver
Mechanical hindfoot angle	0.907 (0.862 to 0.949)	0.921 (0.889 to 0.968)	0.886 (0.837 to 0.919)	0.917 (0.887 to 0.958)
Subtalar vertical angle	0.892 (0.871 to 0.931)	0.949 (0.918 to 0.986)	0.842 (0.815 to 0.886)	0.887 (0.835 to 0.924)
Talar tilt angle	0.953 (0.910 to 0.989)	0.978 (0.967 to 0.985)	0.848 (0.599 to 0.890)	0.890 (0.861 to 0.920)
Distal tibia joint line angle	0.942 (0.880 to 0.989)	0.953 (0.880 to 0.989)	0.834 (0.798 to 0.852)	0.886 (0.824 to 0.901)
Mechanical tibiofemoral angle	0.918 (0.892 to 0.939)	0.921 (0.907 to 0.936)	0.878 (0.855 to 0.899)	0.906 (0.882 to 0.928)
Mechanical tibia angle	0.959 (0.930 to 0.987)	0.961 (0.946 to 0.989)	0.883 (0.864 to 0.913)	0.918 (0.976 to 0.994)
Proximal tibia joint line angle	0.944 (0.911 to 0.969)	0.932 (0.917 to 0.989)	0.928 (0.976 to 0.994)	0.915 (0.989 to 0.927)

Data are reported as interobserver and intraobserver correlation coefficients with 95% CI.

The subtalar joint’s orientation was not associated with an opposing angulation relative to the hindfoot deformity. This suggests that not every hindfoot deformity is compensated for by the subtalar joint, which is in accordance with the findings of a previous study [17]. Future prospective research could help to identify at different time points the key mechanisms of the subtalar joint that determine which patients are able to compensate for hindfoot deformity. Currently, 3-D measurements are available and can be implemented to analyze joint line orientation in greater detail and provide additional assessment of the articular hindfoot configuration and shape, which has demonstrated to be associated with tibiotalar joint osteoarthritis [26, 48, 58].

Does a Hindfoot Deformity Correlate with the Tibial Joint Line’s Orientation in Patients with Tibiotalar Joint Osteoarthritis?

Our data showed a linear increase of the hindfoot angle in correspondence to a decreasing angulation of the tibial joint lines: the hindfoot alignment demonstrated more varus, while the tibial joint lines contained more valgus. The importance of joint line orientation of the tibia towards the hindfoot has been demonstrated after both knee arthroplasty and osteotomy [28, 36]. However, the relation between both was not investigated in detail but is important to assess, particularly in rigid hindfoot deformities that may be aggravated after deformity correction at the knee level [49]. Further studies could assess how joint line orientation differs within hindfoot deformities and how they interfere with corrective treatment either at the level of the knee or hindfoot.

In this cohort, the lower-limb alignment of patients with tibiotalar joint osteoarthritis was associated with varus alignment of the knee in those with a hindfoot valgus deformity and with valgus alignment of the knee in those with a hindfoot varus deformity. Conversely, patients without tibiotalar joint osteoarthritis had similar directions of coronal-plane deviations in the knee and hindfoot. These

distinct radiographic findings were most pronounced in the alignment of the tibia relative to the hindfoot deformity. This suggests a detailed examination of hindfoot alignment before knee deformity correction at the level of the tibia may be valuable, to avoid postoperative increase of pre-existing hindfoot deformity. Other differences detected between the investigated radiographic parameters in this study were less pronounced and varied within the subgroups. Future research could assess patient cohorts prospectively to improve diagnosis by identifying which of the investigated radiographic parameters contain clinical relevance in progressive osteoarthritis or deformity. Treatment strategies could be improved by assessing how and at which level conservative or surgical corrective interventions alter these deformities.

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