JB&JS OPEN ACCESS

Decreased Peritalar Subluxation in Progressive Collapsing Foot Deformity with Ankle Valgus Tilting

Nacime Salomao Barbachan Mansur, MD, PhD, Matthieu Lalevee, MD, MSc, Alan Shamrock, MD, Francois Lintz, MD, MSc, FEBOT, Kepler Alencar Mendes de Carvalho, MD, and Cesar de Cesar Netto, MD, PhD

Investigation performed at the University of Iowa, Iowa City, Iowa

Background: Middle facet subluxation (MFS) has been established as an early indicator of peritalar subluxation. However, when progressive collapsing foot deformity (PCFD) affects the ankle leading to a valgus talar tilt (Class E), structures and anatomic relationships distal to the ankle joint may be affected. Therefore, this study aimed to assess radiographic parameters of peritalar subluxation in patients with PCFD who either did or did not have a valgus ankle. Our hypothesis was that these parameters would differ in Class E patients, upsetting their capability to quantify deformity.

Methods: We performed a prospective comparative study utilizing weight-bearing computed tomography (WBCT) images of 21 feet with PCFD and with valgus of the ankle and 64 with flexible PCFD without ankle involvement. Parameters including MFS, the medial cuneiform-to-floor distance, the forefoot arch angle, the talonavicular coverage angle, the hindfoot moment arm (HMA), the foot-ankle offset (FAO), and the talar tilt angle (TTA) were measured and compared. Variables that influence the presence of ankle valgus and overall alignment were assessed by multivariable regression models.

Results: Patients with PCFD and ankle valgus demonstrated a higher mean HMA (20.79 mm [95% confidence interval (CI), 17.56 to 24.02 mm] versus 8.94 mm [95% CI, 7.09 to 10.79 mm]), FAO (14.89% [95% CI, 12.51% to 17.26%] versus 6.32% [95% CI, 4.96% to 7.68%]) and TTA (95% CI, 17.10° [14.75° to 19.46°] versus 2.30° [95% CI, 0.94° to 3.65°]) and lower mean MFS (21.84% [95% CI, 15.04% to 28.63%] versus 38.45% [95% CI, 34.55% to 42.34%]) compared with the group without ankle valgus ($p < 0.0001$ for all). The FAO was influenced by MFS in the group without ankle valgus ($p < 0.0001$) but not in the group with ankle valgus ($p = 0.9161$). FAO values of ≥12.14% were a strong predictor (79.2%) of ankle valgus deformity.

Conclusions: Subluxation of the middle facet was not as severe and did not influence the overall alignment in patients with PCFD who had valgus of the ankle (Class E). These findings suggest a distal peritalar reduction in the presence of a proximal deformity, making MFS an imprecise disease parameter in this scenario. An FAO value of ≥12.14% was a strong indicator of ankle deformity in patients with PCFD.

Level of Evidence: Diagnostic Level II. See Instructions for Authors for a complete description of levels of evidence.

Peritalar subluxation is a key pathological aspect of progressive collapsing foot deformity (PCFD)[1-3]. It defines the true evolution of the disease, portraying how adjacent bones move around an initially fixed talus[4,5]. The deformity's pivot point at the hindfoot is believed to occur close to the sinus tarsi or the interosseous talocalcaneal ligament and middle facet of the subtalar joint[2,6,7]. Several markers of peritalar subluxation have been described to better diagnose and predict the development of PCFD, such as subluxation of the middle facet of the subtalar joint and foot-ankle offset (FAO)[5,8]. Other aspects of this 3-dimensional (3D) disease might occur concurrently, as defined by the PCFD Consensus Group and the novel PCFD staging system, which describes aspects of the deformity according to classes[9]. Hindfoot valgus (Class A), midfoot abduction (Class B), and forefoot varus/medial column instability (Class C) are common deformities that need consideration when assessing patients with PCFD[10-12].

Proximally, PCFD may affect the ankle joint, producing a valgus instability of the talus inside the mortise, leading to a

Disclosure: The **Disclosure of Potential Conflicts of Interest** forms are provided with the online version of the article (http://links.lww.com/JBJSOA/A565).

valgus talar-tilt deformity (Class E)[13]. The tibiotalar deformity disturbs fixed position of the talus in the coronal plane, changing the fulcrum of deformity from the subtalar to the ankle joint[14,15]. This change could affect the relationship of peritalar structures, which may or may not adapt to a more proximal deformity. Previous studies assessing hindfoot positioning in arthritic and unstable ankles demonstrated a tendency of the subtalar joint to compensate for proximal malignment[16-18]. Wang et al. showed that both valgus (39%) and varus (53%) arthritic ankles exhibited compensatory subtalar positioning in varus and valgus, respectively, and that the compensation would be less likely to happen when arthritis was present in the subtalar joint[17].

Expected accommodative changes in the subtalar joint and peritalar structures once ankle valgus deformity develops might affect traditional diagnostic parameters of PCFD, potentially influencing predictors of disease progression and treatment planning[5,19,20]. Therefore, the primary aim of this study was to evaluate peritalar subluxation, primarily by means of middle facet subluxation (MFS), in patients with PCFD who either did or did not demonstrate ankle valgus. We hypothesized that traditional hallmarks of peritalar subluxation, such as MFS, would be less evident in patients with PCFD with valgus deformity of the ankle, impacting the capability of these parameters to predict PCFD severity, prognosis, and treatment once the ankle joint is involved.

Materials and Methods

Design

This prospective comparative study was approved by the institutional review board (202012422) before data collection, in conformity with the Declaration of Helsinki and the Health Insurance Portability and Accountability Act (HIPAA). The study complied with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines[21].

Sample Size

The sample size was calculated on the basis of the ability to detect a 40% difference in the primary outcome between groups. Baseline values of MFS were extracted from the study by de Cesar Netto et al.[8]. In order to achieve a 0.05 type-I error rate and 90% power (a 0.1 type-II error rate), 21 patients per group would be needed.

Patients

Consecutive patients with a clinical diagnosis of PCFD who were treated at our institution from January 2019 to December 2021 were evaluated. Adults (≥18 years of age) presenting with PCFD history and clinical confirmation and having weight-bearing computed tomography (WBCT) imaging were included. Patients were excluded if they had any rigid deformity (Stage 2) on

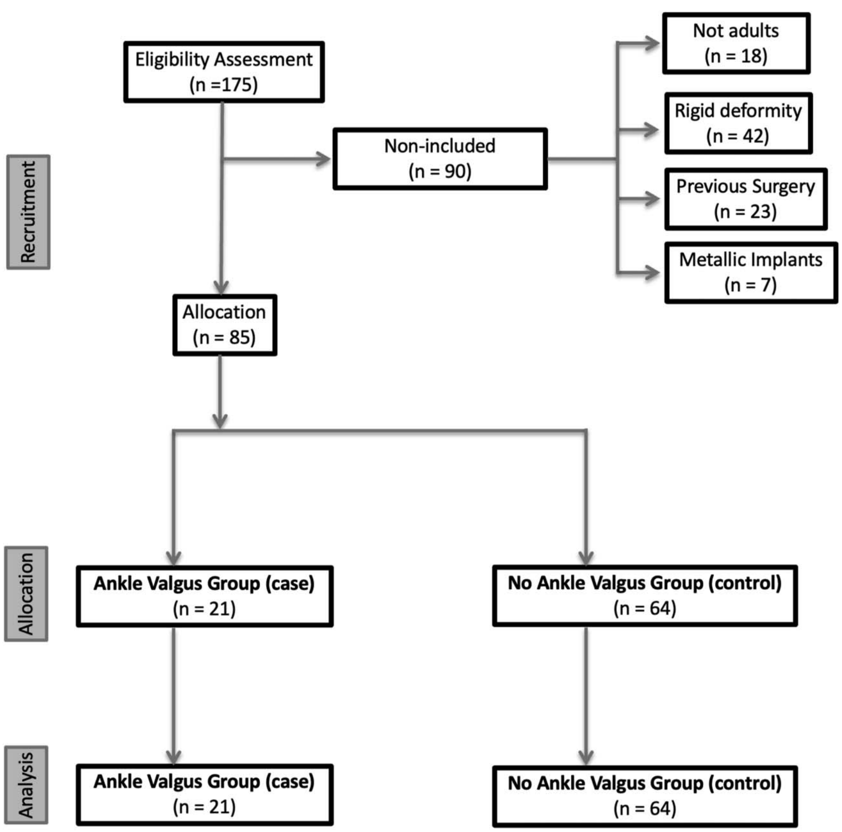

Fig. 1
STROBE flowchart for the study.

examination, a history of ankle trauma, metallic implants, or prior PCFD surgery. The subjects were allocated to study groups as shown in Figure 1.

Group with Ankle Valgus

Patients presenting with Stage 1 (flexible), Class E (ankle instability) PCFD were allocated to the group with ankle valgus[10]. A valgus tilting of the talus of at least 3° on an anteroposterior weight-bearing ankle radiograph was considered indicative of Class E[22,23]. Flexibility was defined by physical examination and fluoroscopy[24]. A total of 21 feet (57.1% left, 42.9% right) in 20 patients (30% female, 70% male) with a mean age of 68.50 years (range, 46 to 91 years) and a body mass index (BMI) of 31.84 kg/m^2 (95% confidence interval [CI], 28.58 to 35.11 kg/m^2) were assigned to this group (Table I).

Group without Ankle Valgus

Patients presenting with any other flexible (Stage 1) class or combination of classes of PCFD with the absence of valgus talar tilt (<3°) were assigned to the group with no ankle valgus[10]. This group consisted of a total of 64 feet (51.6% left, 48.4% right) in 41 patients (71% female, 29% male) with a mean age of 56.27 years (range, 26 to 87 years) and a BMI of 32.76 kg/m^2 (95% CI, 30.84 to 34.69 kg/m^2) (Table I).

WBCT Acquisition

A cone-beam CT extremity scanner (PedCAT; CurveBeam) was utilized to obtain the WBCT studies. Participants were advised to stand upright with the feet a shoulder-width apart, facing directly forward, with body weight evenly distributed between the lower extremities[25,26].

WBCT Measurements

Using dedicated software (CubeVue; CurveBeam), multiplanar data were converted into sagittal, coronal, and axial images. Two fellowship-trained orthopaedic foot and ankle surgeons performed the measurements using previously described methods (Fig. 2)[26].

In the sagittal plane, the medial cuneiform-to-floor distance (MCFD) was measured from the most plantar aspect of the medial cuneiform to the ground plate, portraying the arch collapse (Class C)[26,27]. In the axial plane, the talonavicular coverage angle (TNCA) was calculated using the articular orientations of the talar head and the proximal navicular, depicting midfoot abduction (Class B)[26,28].

MFS was assessed at the facet midpoint in the sagittal plane, representing a direct sign of peritalar subluxation (Class D). The percentage of MFS was quantified by dividing the amount of facet "uncoverage" by the width of the talar facet in the coronal plane[1,8]. The forefoot arch angle (FFA) was established by drawing a line from the most plantar aspect of the medial cuneiform to the plantar cortex of the fifth metatarsal in the coronal view. The angle between this line and the ground determined the FFA, a variable associated with forefoot varus (Class C)[26,29].

To calculate the hindfoot moment arm (HMA), the axis of the tibia was determined using the midpoints at 5 and 10 cm above the ankle joint in the coronal view. First, the distance between the tibial axis line and the most plantar aspect of the calcaneus was defined as the HMA, a hindfoot valgus (Class A) metric[26]. Next, the talar tilt angle (TTA) was measured from the angle between the distal tibial articular surface and the superior talar articular surface, characterizing

TABLE I Group Demographics and Measurement Characteristics

Variable*	Group: Ankle Valgus (N = 21)†	Group: No Ankle Valgus (N = 64)†	P Value	ICC‡
Age *(yr)*	68.50 (62.91-74.09)	56.27 (51.41-61.12)	0.0030§	—
BMI *(kg/m^2)*	31.84 (28.58-35.11)	32.76 (30.84-34.69)	0.5280	—
MCFD *(mm)*	19.32 (17.24-21.41)	17.73 (16.53-18.92)	0.1891	0.977 (0.788-0.994)
TNCA *(deg)*	22.71 (17.46-27.96)	22.58 (19.58-25.59)	0.9669	0.794 (0.558-0.911)
FFA *(deg)*	2.58 (0.19-4.96)	4.25 (2.89-5.63)	0.2280	0.961 (0.906-0.984)
MFS *(%)*	21.84 (15.04-28.63)	38.45 (34.55-42.34)	<0.0001§	0.866 (0.699-0.943)
HMA *(mm)*	20.79 (17.56-24.02)	8.94 (7.09-10.79)	<0.0001§	0.893 (0.757-0.955)
MDTA *(deg)*	87.77 (87.03-88.50)	88.03 (87.61-88.45)	0.5403	0.914 (0.631-0.967)
TTSA *(deg)*	74.01 (71.72-76.30)	89.08 (87.77-90.39)	<0.0001§	0.959 (0.903-0.983)
TTA *(deg)*	17.10 (14.75-19.46)	2.30 (0.94-3.65)	<0.0001§	0.903 (0.725-0.963)
FAO *(%)*	14.89 (12.51-17.26)	6.32 (4.96-7.68)	<0.0001§	0.987 (0.969-0.995)

*BMI = body mass index, MCFD = medial cuneiform-to-floor distance, TNCA = talonavicular coverage angle, FFA = forefoot arch angle, MFS = middle facet subluxation, HMA = hindfoot moment arm, MDTA = medial distal tibial angle, TTSA = tibiotalar surface angle, TTA = talar tilt angle, and FAO = foot-ankle offset. †The values are given as the mean, with the 95% confidence interval in parentheses. ‡Interreader reliability. The values are given as the estimate, with the 95% confidence interval in parentheses. ICC = interclass correlation coefficient. §Significant.

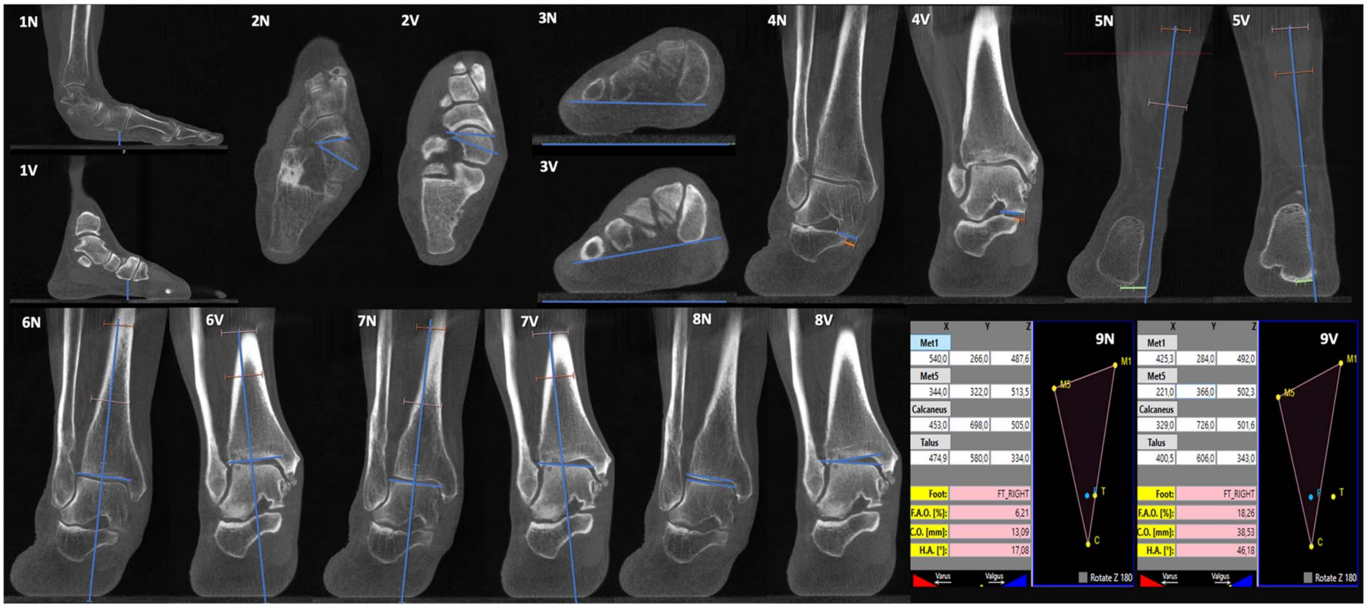

Fig. 2

The sequence of measurements performed in the 2 groups is shown using examples (N = no ankle valgus, and V = valgus). Using the most distal voxel of the medial cuneiform on the sagittal view, the medial cuneiform-to-floor distance (MCFD) was measured: 1N = 16.66 mm, and 1V = 26.13 mm. The talonavicular coverage angle (TNCA) was obtained from the talar and navicular articular axial orientations: 2N = 41.4°, and 2V = 16.1°. Coronally, the forefoot arch angle (FFA) was determined by drawing a line from the most distal voxel of the medial cuneiform to the fifth metatarsal plantar surface and measuring the angle between this line and the ground: 3N = −1.2°, and 3V = 10.1°. Middle facet subluxation (MFS) used the coronal projection of the facet's central point to determine the related uncoverage: 4N = 47.1%, and 4V = 24.36%. The distance between the most distal aspect of the calcaneus and the tibial axis determined the hindfoot moment arm (HMA): 5N = 8.4 mm, and 5V = 5.81 mm. The medial distal tibial angle (MDTA) was obtained from the relation between the tibial axis and distal tibial surface at the center of the ankle: 6N = 88.2°, and 6V = 87.8°. By using the talar dorsal surface and the tibial axis, the tibiotalar surface angle (TTSA) was obtained: 7N = 87.1°, and 7V = 80.8°. The talar tilt angle (TTA) measured the relationship between the distal tibial surface and talar dorsal surface: 8N = 0.3°, and 8V = 11.2°. Finally, foot-ankle offset (FAO) was determined using the talar deviation from the foot tripod center: 9N = 6.21%, and 9V = 18.26%.

ankle valgus tilting (Class E)[17]. The medial distal tibial angle (MDTA) was calculated using the angle between the tibial axis and the distal tibial articular surface[30]. The angle between the tibial axis and the talar articular surface established the tibiotalar surface angle (TTSA)[17].

FAO, a previously validated, 3D measurement of overall PCFD severity, was quantified using dedicated software (TALAS [Torque Ankle Lever Arm System], CubeVue; CurveBeam)[25]. First, the most plantar aspect of the first metatarsal, the most plantar aspect of the fifth metatarsal, and the most plantar aspect of the calcaneal tuberosity were marked, creating the foot tripod. Subsequently, the talar dome center was established. The obtained value represents the percentage of ankle deviation from the tripod's center (Fig. 2). A valgus hindfoot alignment is characterized by a positive percentage, with FAO values of >5.2% considered abnormal[31-33].

Statistical Analysis

Measurements were assessed for normality using the Shapiro-Wilk test. Interobserver reliability was evaluated by interclass correlation coefficients (ICCs). Values of <0.40 were considered poor; 0.40 to 0.59, fair; 0.60 to 0.74, good; and 0.75 to 1.00, excellent. Paired Wilcoxon or paired t tests were utilized for comparisons between the groups. Multivariable regression analyses were performed to evaluate variables influencing the presence or absence of ankle valgus and influencing FAO. Bivariate analyses between significantly correlated variables were also performed. A partition prediction model of significant variables was utilized to assess the threshold of variables associated with ankle valgus deformity[34]. Significance was defined as a p value of <0.05.

Source of Funding

There was no external funding source for this study.

Results

The 2 study groups exhibited similar mean BMI values (p = 0.53); however, the group with ankle valgus was significantly older (p = 0.030) (Table I). The ICCs for interobserver reliability were excellent (≥0.75) for the WBCT measurements. The average TTA (Class E deformity) was 17.10° (95% CI, 14.75° to 19.46°) for the ankle valgus group versus 2.30° (95% CI, 0.94° to 3.65°) for the group with no ankle valgus (p < 0.0001).

When comparing measurements of PCFD deformity severity between the groups, the markers of hindfoot valgus

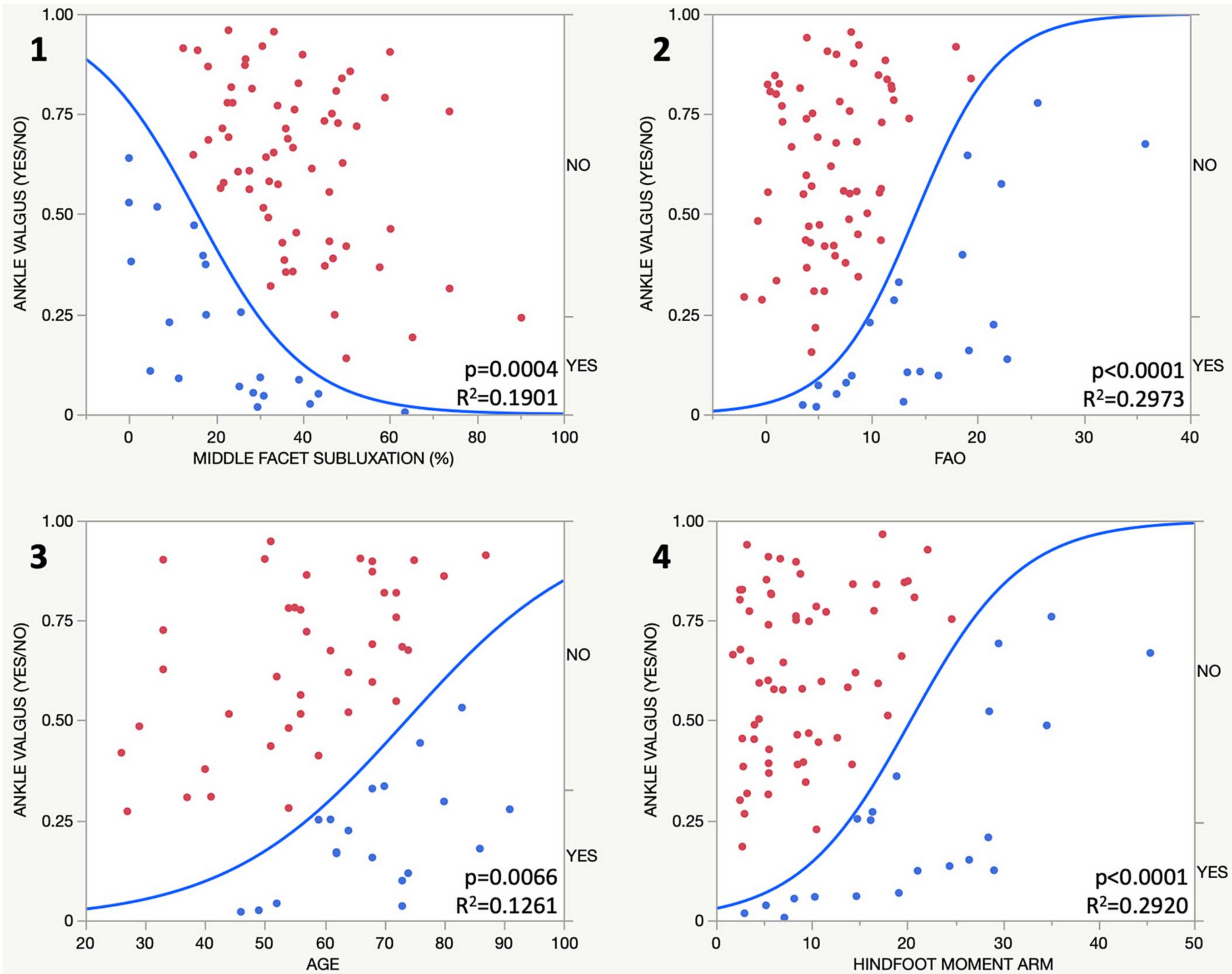

Fig. 3

Bivariate logistic regression analyses of the correlated variables versus the presence of ankle valgus (yes or no), including the respective coefficient of determination (R^2) and p value. The logistic fit for middle facet subluxation (panel 1) shows a significant and negative correlation with the presence of ankle valgus. Foot-ankle offset (FAO, panel 2), age (panel 3), and hindfoot moment arm (panel 4) logistic fits display significant and positive correlations with ankle valgus.

(Class A) and overall 3D deformity were found to be more pronounced in the ankle valgus group, including HMA (mean, 20.79 mm [95% CI, 17.56 to 24.02 mm] versus 8.94 mm [95% CI, 7.09 to 10.79 mm]; $p < 0.0001$) and FAO (mean, 14.89% [95% CI, 12.51% to 17.26%] versus 6.32% [95% CI, 4.96% to 7.68%]; $p < 0.0001$). Nevertheless, the radiographic parameters of peritalar subluxation (Class D) were found to be considerably and significantly less pronounced in the ankle valgus group, which had a mean MFS of 21.84% (95% CI, 15.04% to 28.63%) versus 38.45% (95% CI, 34.55% to 42.34%) in the group with no ankle valgus ($p < 0.0001$). No differences were found between the groups when assessing other components of PCFD, including the TNCA for Class B ($p = 0.9669$) and the MCFD ($p = 0.1891$) and FFA ($p = 0.2280$) for Class C.

In the multivariable analysis, MFS ($p < 0.0001$), FAO ($p = 0.0073$), age ($p = 0.0118$), and HMA ($p = 0.0285$) were found to be the only variables that influenced the presence or absence of ankle valgus deformity (Class E) ($p < 0.0001$), explaining 81% of the variation in ankle alignment ($R^2 = 0.8116$). Results of the bivariate logistic regression analysis for each correlated variable (MFS, FAO, age, and HMA) are shown in Figure 3. In addition, the partition prediction model revealed that FAO values were the strongest predictors of ankle valgus deformity, with FAO values of <12.14% being associated with a 10.5% probability of ankle valgus deformity and FAO values equal or above that threshold being associated with a 79.2% probability of ankle valgus deformity.

When assessing variables that influenced the overall 3D deformity (measured by the FAO) in the patients without ankle valgus deformity, the multivariable regression analysis demonstrated that the HMA ($p < 0.0001$) and MFS ($p < 0.0001$)

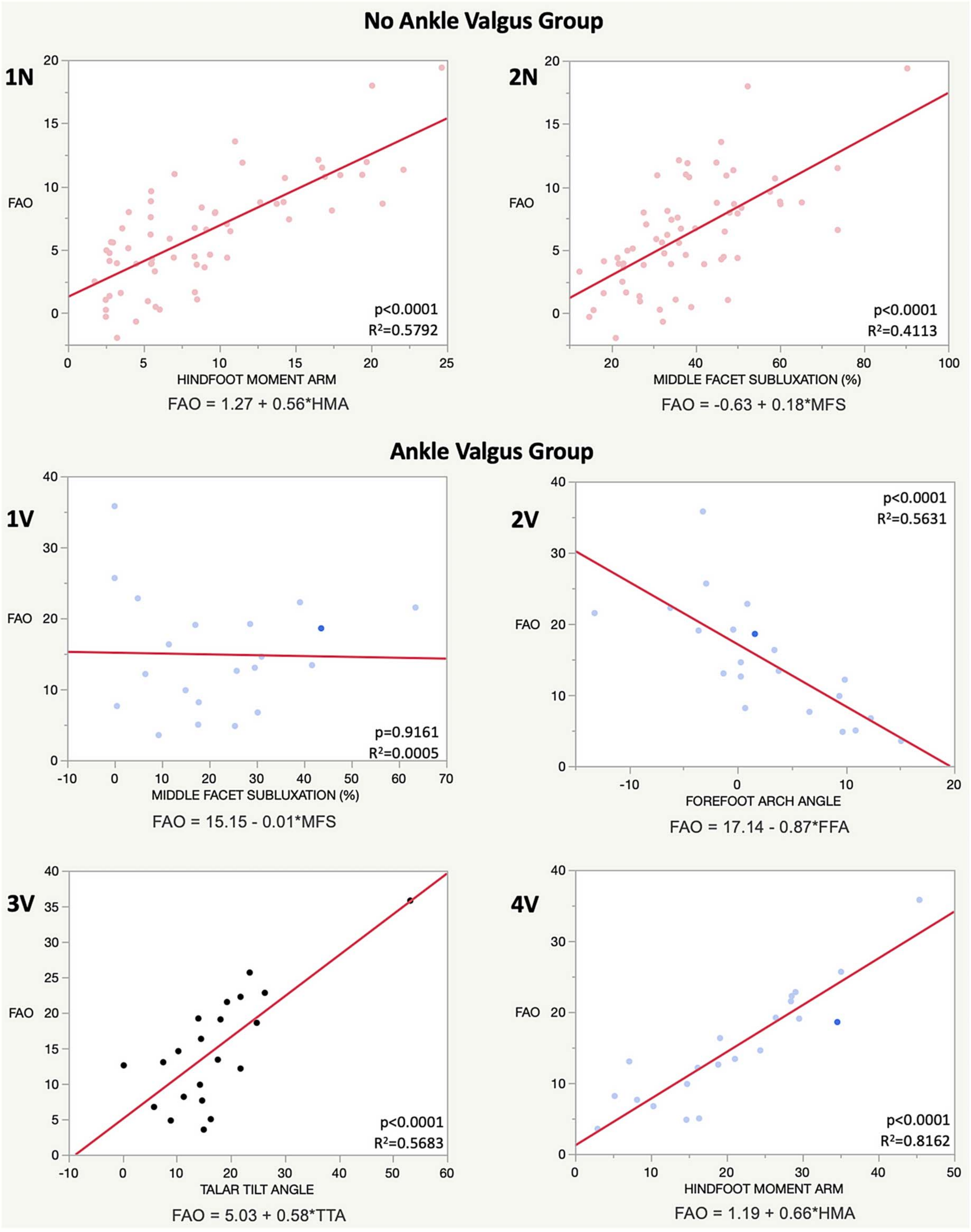

Fig. 4

Bivariate logistic regression analyses of the correlated variables versus foot-ankle offset (FAO) in the groups with no ankle valgus (N) and ankle valgus (V), including the respective coefficient of determination (R^2), p value, and predictive formula derived from the linear fit calculation. The logistic fits for the hindfoot moment arm (HMA, 1N) and middle facet subluxation (MFS, 2N) show a significant and positive correlation with FAO in the group with no ankle valgus. MFS (1V) was not significantly correlated with FAO in the group with ankle valgus, but is presented here to reflect the study's main hypothesis. The forefoot arch angle (FFA, 2V) was significantly and negatively correlated with FAO. In contrast, the talar tilt angle (TTA, 3V) and the HMA (4V) were significantly and positively correlated with FAO in the ankle valgus group.

explained 64% of the variation ($R^2 = 0.6418$; $p < 0.0001$) in FAO. However, in the group with ankle valgus deformity, the multivariable analysis demonstrated that MFS did not correlate with FAO ($p = 0.9161$), and only FFA ($p = 0.0002$), TTA ($p = 0.0054$), and HMA ($p = 0.0055$) correlated with FAO, explaining 94% of its variation ($R^2 = 0.9404$; $p < 0.0001$). The bivariate linear regression analyses for MFS versus the variables significantly correlated with FAO in either group are shown in Figure 4.

Discussion

In this study, radiographic parameters of peritalar subluxation were assessed in patients with PCFD who had valgus of the ankle (Class E) and compared with patients with PCFD who did not have valgus ankle deformity. Mean MFS was found to be lower in the ankle valgus group and unaffected by an increase in overall malalignment (FAO). Furthermore, a strong correlation observed between alignment (FAO) and MFS (peritalar subluxation) in the group without ankle valgus was not seen in the group with ankle valgus. The results corroborate our primary hypothesis. Considering these findings, peritalar subluxation might occur first in PCFD, potentially around the subtalar and midtarsal joints, increasing the load on the deltoid ligament. Conversely, when this overload leads to proximal failure and a valgus talar tilt, we noticed a paradoxical reduction of the peritalar subluxation despite likely underlying peritalar ligamentous incompetence.

The search for a parameter that reliably predicts peritalar subluxation early in the disease process led Ananthakrisnan et al. and de Cesar Netto et al. to study coverage of the subtalar facets[2,8]. The former found differences in interactions between controls and patients with PCFD when analyzing the posterior facet (92% versus 68%) and the medial or anterior facets (95% versus 51%)[2]. By assessing the middle facet under WBCT, de Cesar Netto et al. found higher uncoverage values in patients with PCFD (45.3%) compared with controls (4.8%) and found that values of >17.9% had high sensitivity (96.7%) and specificity (100%) for disease diagnosis[8]. More recently, Dibbern et al., using 3D distance and coverage maps, found a 47% decrease in middle facet coverage in patients with PCFD[35]. In the group with PCFD and no ankle valgus in the current study, a mean MFS of 38.45% was demonstrated, which is in line with the previous reports and supports its use as a marker of peritalar subluxation in this population. A lower mean MFS value was seen in the group with ankle valgus (21.84%), which could be explained by a peritalar reduction.

The concept was explored by Wang et al. when evaluating subtalar joint behavior in patients with maligned ankles[17]. The authors found that 53% of patients with ankle varus and 39% with ankle valgus exhibited distal compensation, assessed by the tibiocalcaneal axis angle[17]. The presence of subtalar arthritis decreased distal compensation to 9% in the valgus group[17]. Krähenbühl et al. evaluated subtalar alignment using WBCT for patients with ankle osteoarthritis and found that varus ankles had a more valgus orientation of the calcaneus posterior facet compared with controls[18]. Valgus ankles, although having a much more pronounced valgus position of the talus, did not differ from controls in subtalar inclination[18]. In contrast, when studying sagittal (talocalcaneal angle) and axial (talus-first metatarsal angle) alignments in the setting of ankle deformities, Nosewicz et al. did not find predictable deformities or signs of direct coronal compensation[16]. In the ankle valgus group, those authors observed 48% of malposition in other planes, mainly neutral or plantar flexion of the talus in the sagittal plane combined with neutral or external rotation in the axial plane[16]. Unlike our cohort, patients with primary ankle deformities might experience an actual distal deformity compensation. In PCFD, the initial pathological configuration of peritalar subluxation may be "reduced" to a physiological position when the ankle fails, in an intrinsic attempt to keep the foot plantigrade.

In our group with ankle valgus, worse hindfoot (HMA, 20.79 versus 8.94 mm) and 3D positions (FAO, 14.89% versus 6.32%) revealed that the overall malalignment was greater in this population. Further research is needed to confirm these concepts. Still, the lower mean MFS could be a sign that distal reduction is occurring and that the peritalar joints are therefore flexible and, potentially, candidates for reconstruction. Ankle deformity correction in such cases (through reconstruction, replacement, or arthrodesis) might lead to reintroduction of peritalar subluxation parameters, which could be clinically (and surgically) relevant when treating Class E patients.

Our results showed that MFS could not be used as a radiographic parameter of peritalar subluxation or deformity severity in Class E patients. These results in patients with ankle valgus contrapose the findings of a previous study by our group, which described the influence of MFS on FAO values in PCFD without ankle valgus[5]. Lintz et al. also described the MFS and FAO relationship in PCFD without ankle valgus by showing the highest accuracies for disease diagnosis using these metrics in isolation and when combined (100% sensitivity and 100% specificity)[36]. On the basis of our findings, FAO, HMA, and TAA are the imaging parameters most predictive of disease severity and progression in patients with Class E PFCD (Fig. 4). Moreover, FAO values of ≥12.14% were found to be associated with a 79.2% probability of ankle valgus deformity. This could be beneficial in the clinical scenario by providing a value for identifying patients with a higher risk of ankle involvement. To our knowledge, the only study that tried to predict ankle deformity in PCFD was performed by Miniaci-Coxhead et al., who found that an increased talus-first metatarsal angle preoperatively was associated with the development of talar tilt after hindfoot fusion (hazard ratio, 1.034)[37].

The present study had several limitations. Although it was a prospective study, we could not evaluate the true linear evolution of PCFD over time. This is important for Class E deformities that might present earlier than anticipated[10,24,38]. Although patients had a history of PCFD and no ankle trauma, it is impossible to completely exclude the possibility that an ankle deformity could have occurred first. No functional assessment was performed, making it impossible to relate the findings to clinical symptoms and presentation. Stage 2 (rigid) subjects were not included in this cohort, and thus our conclusions are not applicable to that PCFD population. The complete lower-extremity alignment and its effects were not assessed, but those additional factors that could have influenced foot and ankle positions. The groups were not perfectly matched; patients in the group with ankle valgus were older than those without valgus, a difference that is probably explained by the natural history of this deformity, in which talar tilt occurs later than peritalar subluxation. Finally, the use of WBCT is still not widespread, decreasing the study's reproducibility.

Conclusions

In patients with PCFD and valgus of the ankle (Class E), MFS values were significantly lower than in those without valgus of the ankle and did not correlate with overall malalignment. Peritalar subluxation might be reduced in this group of patients since the deformity fulcrum changed proximally. Consequently, MFS should not be used as an imaging parameter to evaluate and stage Class E patients. A high probability of ankle valgus deformity was associated with FAO values of ≥12.14% in PCFD. ■

Nacime Salomao Barbachan Mansur, MD, PhD[1,2]
Matthieu Lalevee, MD, MSc[1,3]
Alan Shamrock, MD[1,4]
Francois Lintz, MD, MSc, FEBOT[5]
Kepler Alencar Mendes de Carvalho, MD[1]
Cesar de Cesar Netto, MD, PhD[1,6]

[1]Department of Orthopedics and Rehabilitation, Carver College of Medicine, University of Iowa, Iowa City, Iowa

[2]Department of Orthopedics and Traumatology, Escola Paulista de Medicina, Universidade Federal de São Paulo, São Paulo, Brazil

[3]Service d'orthopédie Traumatologie, Centre Hospitalier Universitaire de Rouen, Rouen, France

[4]Hospital for Special Surgery, New York, NY

[5]Clinique de L'Union, Saint-Jean-le-Blanc, France

[6]Division of Foot and Ankle Surgery, Department of Orthopaedic Surgery, Duke University Health System, Duke University, Durham, North Carolina

Email for corresponding author: cesar-netto@uiowa.edu

References

1. de Cesar Netto C, Silva T, Li S, Mansur NS, Auch E, Dibbern K, Femino JE, Baumfeld D. Assessment of Posterior and Middle Facet Subluxation of the Subtalar Joint in Progressive Flatfoot Deformity. Foot Ankle Int. 2020 Oct;41(10):1190-7.
2. Ananthakrisnan D, Ching R, Tencer A, Hansen ST Jr, Sangeorzan BJ. Subluxation of the talocalcaneal joint in adults who have symptomatic flatfoot. J Bone Joint Surg Am. 1999 Aug;81(8):1147-54.
3. Toolan BC, Sangeorzan BJ, Hansen ST Jr. Complex reconstruction for the treatment of dorsolateral peritalar subluxation of the foot. Early results after distraction arthrodesis of the calcaneocuboid joint in conjunction with stabilization of, and transfer of the flexor digitorum longus tendon to, the midfoot to treat acquired pes planovalgus in adults. J Bone Joint Surg Am. 1999 Nov;81(11):1545-60.
4. Apostle KL, Coleman NW, Sangeorzan BJ. Subtalar joint axis in patients with symptomatic peritalar subluxation compared to normal controls. Foot Ankle Int. 2014 Nov;35(11):1153-8.
5. Barbachan Mansur NS, Lalevee M, Maly C, Dibbern K, Lee HY, Godoy-Santos AL, Lintz F, de Cesar Netto C. Association Between Middle Facet Subluxation and Foot and Ankle Offset in Progressive Collapsing Foot Deformity. Foot Ankle Int. 2022 Jan;43(1):96-100.
6. Mittlmeier T, Rammelt S. Update on Subtalar Joint Instability. Foot Ankle Clin. 2018 Sep;23(3):397-413.
7. Peña Fernández M, Hoxha D, Chan O, Mordecai S, Blunn GW, Tozzi G, Goldberg A. Centre of Rotation of the Human Subtalar Joint Using Weight-Bearing Clinical Computed Tomography. Sci Rep. 2020 Jan 23;10(1):1035.
8. de Cesar Netto C, Godoy-Santos AL, Saito GH, Lintz F, Siegler S, O'Malley MJ, Deland JT, Ellis SJ. Subluxation of the Middle Facet of the Subtalar Joint as a Marker of Peritalar Subluxation in Adult Acquired Flatfoot Deformity: A Case-Control Study. J Bone Joint Surg Am. 2019 Oct 16;101(20):1838-44.
9. de Cesar Netto C, Deland JT, Ellis SJ. Guest Editorial: Expert Consensus on Adult-Acquired Flatfoot Deformity. Foot Ankle Int. 2020 Oct;41(10):1269-71.
10. Myerson MS, Thordarson DB, Johnson JE, Hintermann B, Sangeorzan BJ, Deland JT, Schon LC, Ellis SJ, de Cesar Netto C. Classification and Nomenclature: Progressive Collapsing Foot Deformity. Foot Ankle Int. 2020 Oct;41(10):1271-6.
11. Thordarson DB, Schon LC, de Cesar Netto C, Deland JT, Ellis SJ, Johnson JE, Myerson MS, Sangeorzan BJ, Hintermann B. Consensus for the Indication of Lateral Column Lengthening in the Treatment of Progressive Collapsing Foot Deformity. Foot Ankle Int. 2020 Oct;41(10):1286-8.
12. Johnson JE, Sangeorzan BJ, de Cesar Netto C, Deland JT, Ellis SJ, Hintermann B, Schon LC, Thordarson DB, Myerson MS. Consensus on Indications for Medial Cuneiform Opening Wedge (Cotton) Osteotomy in the Treatment of Progressive Collapsing Foot Deformity. Foot Ankle Int. 2020 Oct;41(10):1289-91.
13. Bluman EM, Myerson MS. Stage IV posterior tibial tendon rupture. Foot Ankle Clin. 2007 Jun;12(2):341-62, viii.
14. Brodell JD Jr, MacDonald A, Perkins JA, Deland JT, Oh I. Deltoid-Spring Ligament Reconstruction in Adult Acquired Flatfoot Deformity With Medial Peritalar Instability. Foot Ankle Int. 2019 Jul;40(7):753-61.
15. Sangeorzan A, Sangeorzan B. Subtalar Joint Biomechanics: From Normal to Pathologic. Foot Ankle Clin. 2018 Sep;23(3):341-52.
16. Nosewicz TL, Knupp M, Bolliger L, Henninger HB, Barg A, Hintermann B. Radiological morphology of peritalar instability in varus and valgus tilted ankles. Foot Ankle Int. 2014 May;35(5):453-62.
17. Wang B, Saltzman CL, Chalayon O, Barg A. Does the subtalar joint compensate for ankle malalignment in end-stage ankle arthritis? Clin Orthop Relat Res. 2015 Jan;473(1):318-25.
18. Krähenbühl N, Siegler L, Deforth M, Zwicky L, Hintermann B, Knupp M. Subtalar joint alignment in ankle osteoarthritis. Foot Ankle Surg. 2019 Apr;25(2):143-9.
19. Hintermann B, Deland JT, de Cesar Netto C, Ellis SJ, Johnson JE, Myerson MS, Sangeorzan BJ, Thordarson DB, Schon LC. Consensus on Indications for Isolated Subtalar Joint Fusion and Naviculocuneiform Fusions for Progressive Collapsing Foot Deformity. Foot Ankle Int. 2020 Oct;41(10):1295-8.
20. Lalevée M, Barbachan Mansur NS, Rojas EO, Lee HY, Ahrenholz SJ, Dibbern KN, Lintz F, de Cesar Netto C. Prevalence and pattern of lateral impingements in the progressive collapsing foot deformity. Arch Orthop Trauma Surg. 2023 Jan;143(1):161-8.
21. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP; STROBE Initiative. Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. BMJ. 2007 Oct 20;335(7624):806-8.
22. Smith JT, Bluman EM. Update on stage IV acquired adult flatfoot disorder: when the deltoid ligament becomes dysfunctional. Foot Ankle Clin. 2012 Jun;17(2):351-60.
23. Leith JM, McConkey JP, Li D, Masri B. Valgus stress radiography in normal ankles. Foot Ankle Int. 1997 Oct;18(10):654-7.
24. Deland JT, Ellis SJ, Day J, de Cesar Netto C, Hintermann B, Myerson MS, Sangeorzan BJ, Schon LC, Thordarson DB, Johnson JE. Indications for Deltoid and Spring Ligament Reconstruction in Progressive Collapsing Foot Deformity. Foot Ankle Int. 2020 Oct;41(10):1302-6.
25. de Cesar Netto C, Bang K, Mansur NS, Garfinkel JH, Bernasconi A, Lintz F, Deland JT, Ellis SJ. Multiplanar Semiautomatic Assessment of Foot and Ankle Offset in Adult Acquired Flatfoot Deformity. Foot Ankle Int. 2020 Jul;41(7):839-48.
26. de Cesar Netto C, Schon LC, Thawait GK, da Fonseca LF, Chinanuvathana A, Zbijewski WB, Siewerdsen JH, Demehri S. Flexible Adult Acquired Flatfoot Deformity: Comparison Between Weight-Bearing and Non-Weight-Bearing Measurements Using Cone-Beam Computed Tomography. J Bone Joint Surg Am. 2017 Sep 20;99(18):e98.
27. Arangio GA, Wasser T, Rogman A. Radiographic comparison of standing medial cuneiform arch height in adults with and without acquired flatfoot deformity. Foot Ankle Int. 2006 Aug;27(8):636-8.
28. Sangeorzan BJ, Mosca V, Hansen ST Jr. Effect of calcaneal lengthening on relationships among the hindfoot, midfoot, and forefoot. Foot Ankle. 1993 Mar-Apr;14(3):136-41.

29. Ferri M, Scharfenberger AV, Goplen G, Daniels TR, Pearce D. Weightbearing CT scan of severe flexible pes planus deformities. Foot Ankle Int. 2008 Feb;29(2):199-204.

30. Barg A, Harris MD, Henninger HB, Amendola RL, Saltzman CL, Hintermann B, Anderson AE. Medial distal tibial angle: comparison between weightbearing mortise view and hindfoot alignment view. Foot Ankle Int. 2012 Aug;33(8):655-61.

31. Zhang JZ, Lintz F, Bernasconi A, Zhang S; Weight Bearing CT International Study Group. 3D Biometrics for Hindfoot Alignment Using Weightbearing Computed Tomography. Foot Ankle Int. 2019 Jun;40(6):720-6.

32. Lintz F, Welck M, Bernasconi A, Thornton J, Cullen NP, Singh D, Goldberg A. 3D Biometrics for Hindfoot Alignment Using Weightbearing CT. Foot Ankle Int. 2017 Jun;38(6):684-9.

33. Lintz F, Barton T, Millet M, Harries WJ, Hepple S, Winson IG. Ground Reaction Force Calcaneal Offset: A new measurement of hindfoot alignment. Foot Ankle Surg. 2012 Mar;18(1):9-14.

34. Jordan C, Livingstone V, Barry D. Statistical modelling using product partition models. Stat Model. 2007;7(3):275-95.

35. Dibbern KN, Li S, Vivtcharenko V, Auch E, Lintz F, Ellis SJ, Femino JE, de Cesar Netto C. Three-Dimensional Distance and Coverage Maps in the Assessment of Peritalar Subluxation in Progressive Collapsing Foot Deformity. Foot Ankle Int. 2021 Jun;42(6):757-67.

36. Lintz F, Bernasconi A, Li S, Lalevée M, Fernando C, Barg A, Dibbern K, de Cesar Netto C. Diagnostic accuracy of measurements in progressive collapsing foot deformity using weight bearing computed tomography: A matched case-control study. Foot Ankle Surg. 2022 Oct;28(7):912-8.

37. Miniaci-Coxhead SL, Weisenthal B, Ketz JP, Flemister AS. Incidence and Radiographic Predictors of Valgus Tibiotalar Tilt After Hindfoot Fusion. Foot Ankle Int. 2017 May;38(5):519-25.

38. Lalevée M, Barbachan Mansur NS, Schmidt E, Carvalho K, Vandelune C, Bernasconi A, Wilken J, de Cesar Netto C. Does tibialis posterior dysfunction correlate with a worse radiographic overall alignment in progressive collapsing foot deformity? A retrospective study. Foot Ankle Surg. 2022 Oct;28(7):995-1001.