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Weightbearing Radiographic Predictors of Middle Facet Subluxation in Progressive Collapsing Foot Deformity

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Abstract

Background: Middle facet subluxation (MFS) of the subtalar joint is a key indicator of peritalar subluxation in progressive collapsing foot deformity (PCFD). Although its assessment relies on weightbearing computed tomography (WBCT), it remains unclear which weightbearing radiographic (WBR) measurements correlate with MFS. We hypothesize that radiographic parameters assessing hindfoot alignment are correlated with MFS.

Methods: Seventy-three feet diagnosed with PCFD were evaluated using WBR and WBCT. Five parameters were measured in both modalities: talonavicular coverage (TNC) angle, hindfoot moment arm (HMA), talo–first metatarsal angle, calcaneal pitch angle, and sinus tarsi impingement. MFS was then measured on WBCT. Multivariate and bivariate regression analyses were used to identify which WBR measurements predict or correlate with MFS. Partition analysis was used to identify cutoff values for WBR measurements linked with MFS.

Results: Multivariate regression identified TNC angle and HMA as combined MFS predictors ($R^2 = 0.524$, $P < .0001$). In the bivariate analysis, TNC angle demonstrated a moderate individual correlation with MFS ($r = 0.68$), whereas HMA showed a weak individual correlation ($r = 0.39$). Partition analysis identified practical radiographic thresholds (TNC angle $\geq$ 38 degrees, HMA $\geq$ 11.4 mm) for MFS $\geq$ 18% yet these thresholds explained only 27.3% of variability ($R^2 = 0.273$).

Conclusion: TNC angle and HMA are the most useful WBR measurements for identifying MFS in PCFD. In settings without WBCT access, these offer a practical assessment tool, associated with MFS $\geq$ 18%; however, these cutoffs accounted for only 27.3% of variance ($R^2 = 0.273$), underscoring residual unexplained factors.

Level of Evidence: Level III, retrospective comparative study.

Keywords: progressive collapsing foot deformity, middle facet subluxation, weightbearing radiographs, weightbearing computed tomography, flatfoot

Introduction

Progressive collapsing foot deformity (PCFD) is a complex 3-dimensional deformity characterized by various degrees of hindfoot valgus, forefoot abduction, and midfoot varus.[1] Because of its complexity, advanced imaging modalities such as magnetic resonance imaging and weightbearing computed tomography (WBCT) are required for precise diagnosis and better understanding of the condition.[2-5]

A crucial aspect of PCFD is peritalar subluxation (PTS), which causes dysfunction of the triple joint complex and leads to external rotation, eversion, and abduction of the foot relative to the talus.[6,7] Its significance was highlighted in the 2020 PCFD Consensus Classification system, where it was designated as class D.[1] PTS evaluation is based on 2 principal parameters: subfibular impingement, correlated with late-stage disease,[8] and middle facet subluxation (MFS), which has been reported as indicative of early PTS with a threshold of 18% subluxation.[9] These findings are supported by the anatomical observation that the subtalar joint's rotational axis in PCFD is located laterally, resulting in greater subluxation of the anterior and middle facets compared with the posterior facet.[10]

Given the inherent limitations of conventional radiography in assessing the coronal plane of the hindfoot, WBCT is used primarily to evaluate these PTS markers. A recent study found correlations between talonavicular coverage (TNC) angle and hindfoot moment arm (HMA) measured on weightbearing radiography and lateral bony impingement assessed with WBCT.[11] However, the relationship between weightbearing radiographic (WBR) parameters and MFS is still uncertain. Although WBCT is advantageous for assessing MFS, its limited global availability, especially in resource-limited regions, creates a clear need to validate reliable radiographic alternatives.[12]

This study aims to identify WBR parameters that correlate with or predict MFS in PCFD patients. We hypothesize that WBR parameters assessing the hindfoot alignment could provide a practical alternative for evaluating MFS in this population.

Material and Methods

A retrospective Level III comparative cohort study, approved by our institutional review board (IRB number Pro00113556), was conducted at a single institution. We evaluated patients diagnosed with PCFD between February 2022 and May 2024 who underwent both standing conventional WBR and WBCT (CurveBeam LLC, Warrington, PA) assessments of the foot and ankle. For WBCT scans, standardization of foot positioning involved aligning the heel and second toe along a straight, anterior-directed reference line, corresponding to a neutral (0 degrees) foot orientation.

Exclusion criteria included (1) a history of prior foot or ankle surgery and (2) age less than 19 years. The control group comprised volunteers with no history of foot or ankle symptoms, surgery, or deformities. Patients who met the inclusion criteria were evaluated without stratification for interpatient variability. In cases of bilateral PCFD, each foot was assessed independently.

Radiographic Measurements

We selected 4 widely used and validated radiographic measurements,[2,3] each corresponding to a specific class defined by the 2020 PCFD consensus.[1] Recognizing the lack of defined radiographic measures for assessing class D (PTS), we also included evaluation of sinus tarsi impingement (STI), as a binary variable. The purpose of selecting these measurements was to provide a structured evaluation of each component of the deformity.

For class A, the hindfoot moment arm (HMA) was measured on the hindfoot alignment (Saltzman) view[13] as the horizontal distance (mm) from the tibial axis (connecting midpoints at 5 cm and 10 cm above the ankle) to the most distal heel contact (Figure 1A).

For class B, the TNC angle was measured on the anteroposterior foot view as the angle between lines connecting medial and lateral margins of talar and navicular surfaces (Figure 1B).

Class C was evaluated on the lateral view. The lateral talo–first metatarsal angle (Meary angle) was measured by drawing a line along the longitudinal axes of the talus and first metatarsal. The angle formed at their intersection was recorded. Additionally, the calcaneal pitch angle was also measured as the angle between a line along the inferior border of the calcaneus and a horizontal reference line parallel to the floor (Figure 1C).

Class D was evaluated via STI, as a binary variable (yes/no). STI was considered present when radiographic evidence of bony contact or overlap between the calcaneal and talar surfaces in the sinus tarsi region was observed (Figure 1C). For reliability, all measurements were repeated by the first author 1 week after the initial evaluation for intraobserver analysis. Interobserver reliability was evaluated by a second trained foot and ankle fellow who independently repeated all measurements.

WBCT Measurements

All measurements in WBCT images were performed using a dedicated software (Cubevue, CurveBeam) with the slab tool. The same 4 parameters measured on WBR were evaluated in WBCT images (Figure 2) following the described methodoly[14]: the TNC angle was measured on the axial view, the calcaneal pitch angle and the lateral talo–first

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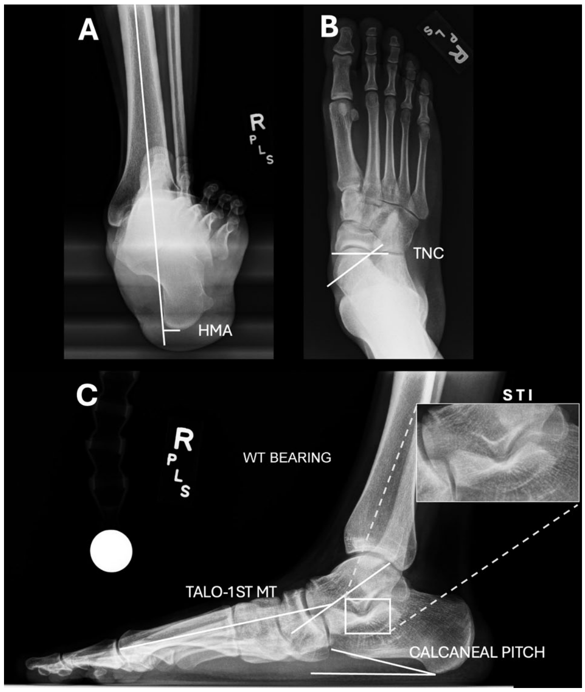

Figure 1. Illustration of radiographic measurements. (A) Hindfoot moment arm (HMA, class A). (B) Talonavicular coverage angle (TNC, class B). (C) Talo–first metatarsal angle and calcaneal pitch angle (class C), and sinus tarsi impingement (STI, class D). Measurement methods are described in the Radiographic Measurements subsection of Methods.

metatarsal angle were measured on the sagittal view, and the HMA in the coronal view. Unlike WBR, STI assessment in WBCT was directly observed in the coronal plane.

The MFS was quantified using the established methodology[9] (Figure 3). First, the maximum anteroposterior length of the middle facet of the subtalar joint was identified in the sagittal plane. The midpoint was identified, and vertical and horizontal reference lines were placed at this point. Finally, the coronal view was aligned using multiplanar reconstruction and crossing planes to determine the amount of uncoverage between the talar and calcaneal surfaces at the middle facet. This measurement is then converted into a percentage.

Statistical Analysis

No missing data were encountered; complete clinical, radiographic, and weightbearing data were available for all included patients. The data's normality was assessed using the Shapiro-Wilk test and Anderson-Darling test. To capture the full clinical range of PCFD, all measured values were used in analyses without outlier exclusion. Significant differences between groups were determined using either Student *t* tests or Wilcoxon rank-sum tests. Intraobserver and interobserver reliability were determined using intraclass correlation coefficients (ICCs) interpreted according to Landis and Koch,[15] with values ranging from 0.81 to 0.99 indicating almost perfect reliability, 0.61 to 0.80 substantial reliability, 0.41 to 0.60 moderate reliability, 0.21 to 0.40 fair reliability, with values less than 0.20 indicating slight reliability.

To extensively investigate radiographic predictors of MFS, we conducted 3 separate but complementary analyses. First, a multiple regression model with all WBR measurements and MFS values was performed to identify combined predictive factors. Among 73 PCFD feet (53 unilateral, 20 from 10 bilateral patients), analyses used one foot per patient to ensure independence. For bilateral cases, the foot with greater middle facet subluxation was selected ($n=63$). Sensitivity analysis comparing this approach to the full sample size (73) showed virtually identical results. Second, bivariate analyses were conducted to examine the individual correlations between each WBR parameter and MFS, using Pearson correlation coefficients for continuous variables and point-biserial correlation coefficients for binary variables. Finally, partition analysis was implemented to establish clinically relevant cutoff values for WBR measurements in predicting MFS $\geq$ 18%, threshold associated with early peritalar subluxation.[9] All statistical analyses were performed using JMP Pro 17.2.0 (SAS Institute Inc, Cary, NC, USA).

A post hoc power analysis was performed using G*Power 3.1 to evaluate sample size adequacy. Based on the directional hypothesis of lower radiographic values in controls, a 1-tailed independent *t* test was applied. With an assumed effect size $d=0.4$, $\alpha=0.05$, and group sizes of 73 (patients) and 20 (controls), the achieved power was 0.62, indicating moderate sensitivity for medium effects.

Results

The flow of participants through the study is summarized in Figure 4. A total of 63 patients with PCFD were included in this study. Ten patients presented with bilateral involvement, resulting in 73 affected feet for analysis. The control group consisted of 20 feet from 10 asymptomatic volunteers. Demographic characteristics are summarized in Table 1.

Weightbearing Radiographic Measurements

The radiographic evaluation demonstrated marked differences between the PCFD and control groups. In the PCFD cohort, the mean TNC angle measured 35.7 degrees, compared with 5.2 degrees in controls ($P<.0001$). Similarly, the talo–first metatarsal angle averaged 26 degrees among

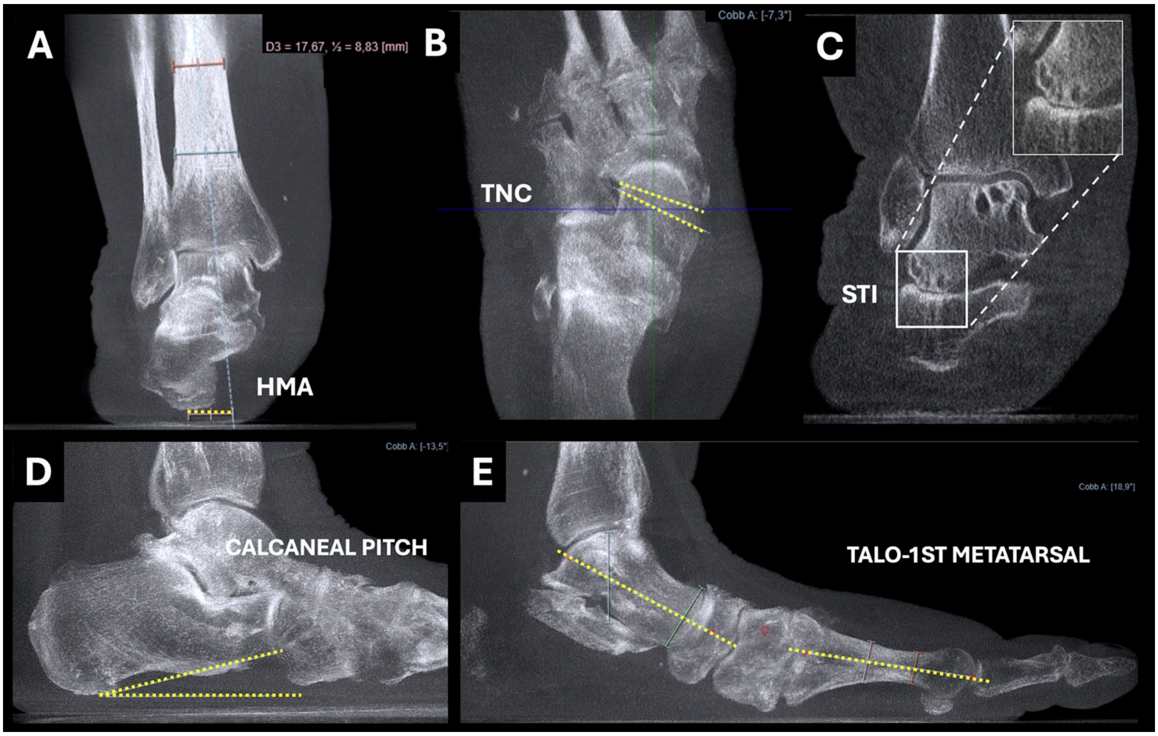

Figure 2. Illustration of measurements in weightbearing computed tomography (WBCT). (A) Hindfoot moment arm (HMA, coronal view). (B) Talonavicular coverage angle (TNC, axial view). (C) Sinus tarsi impingement (STI, coronal view). (D) Calcaneal pitch and (E) talo–first metatarsal angle (sagittal view). Measurement protocol is described in the WBCT Measurements subsection of Methods.

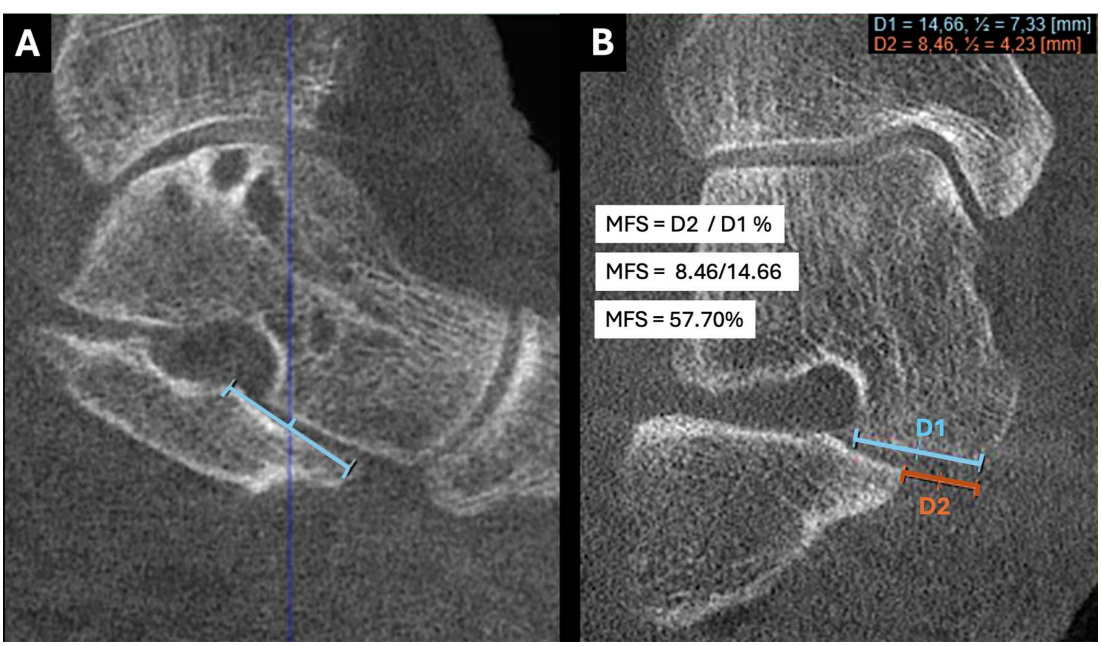

Figure 3. Assessment of middle facet subluxation. (A) Sagittal view: identification of the middle-facet length and placement of reference lines at its midpoint (B) Coronal view: assessment of talocalcaneal coverage at the middle facet, expressed as a percentage. The full measurement protocol is described in the WBCT Measurements subsection of Methods.

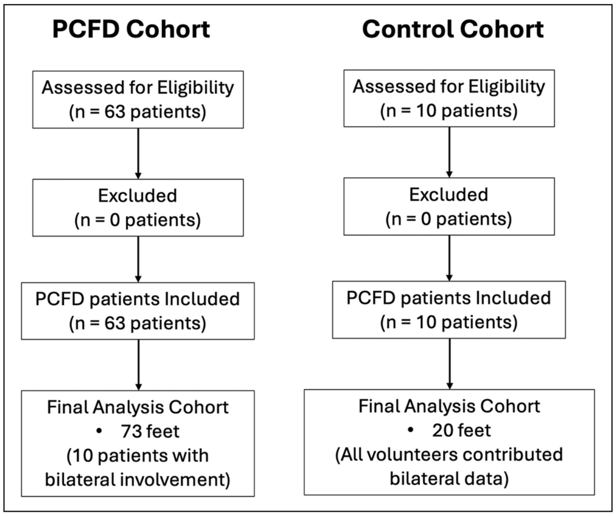

Figure 4. Flow diagram of patient and control inclusion.

Table 1. Demographic Characteristics of Progressive Collapsing Foot Deformity Cases and Controls.

	PCFD Cases	Controls
Number of feet, n	73	20
Laterality: right/left, n (%)	41 (56) / 32 (44)	10 (50) / 10 (50)
Age, y, mean ± SD	59.15 ± 15.63	39.2 ± 6.44
Sex: female/male, n (%)	44 (60) / 29 (40)	6 (30) / 14 (70)
BMI, mean ± SD	32.65 ± 6.35	25.09 ± 2.43
Race, n (%)		
Caucasian	52 (71)	10 (50)
Black	17 (23)	
Other	2 (3)	10 (50)
Asian	1 (1)	
None reported	1 (1)	

Abbreviations: BMI, body mass index; PCFD, progressive collapsing foot deformity; SD, standard deviation.

PCFD cases vs −1.5 degrees in the control group ($P < .0001$). HMA in PCFD patients showed a mean value of 12.43 mm relative to 1.9 mm in controls ($P < .0001$). STI was identified in 60% of the PCFD group but was completely absent in the control group ($P < .0001$).

The reliability assessment of radiographic measurements, presented in Table 2, revealed substantial to almost perfect intraobserver agreement, with ICC ranging from 0.71 to 0.93. Interobserver reliability ranged from moderate to almost perfect (ICC: 0.66-0.82). TNC angle and talo–first metatarsal angle had the highest measurement consistency, particularly for intraobserver assessments where ICC values exceeded 0.85. The evaluation of STI showed the lowest reliability, although the interobserver ICC of 0.66 still represented substantial agreement according to the criteria established by Landis and Koch.[15]

Table 2. Intraclass Correlation Coefficients for Interobserver and Intraobserver Reliability of Radiographic Measurements.

Radiographic Measurements[a]	Intraobserver ICC (95% CI)	Interobserver ICC (95% CI)
Talonavicular coverage angle	0.93 (0.89-0.96)	0.78 (0.49-0.89)
Talo–first metatarsal angle	0.92 (0.87-0.95)	0.77 (0.66-0.85)
Hindfoot moment arm	0.71 (0.43-0.86)	0.72 (0.39-0.88)
Calcaneal inclination angle	0.84 (0.75-0.89)	0.82 (0.73-0.88)
Sinus tarsi impingement	0.82 (0.73-0.88)	0.66 (0.52-0.8)

Abbreviation: ICC, intraclass correlation coefficient.
[a]Radiographic measurements reached good to excellent intraobserver reliability (ICC range: 0.71-0.93) and moderate to excellent interobserver reliability (ICC range: 0.66-0.82). TNC angle and talo–first metatarsal angle showed the highest consistency, whereas STI had the lowest interobserver agreement, though still within an acceptable range.

Weightbearing Tomographic Measurements

Table 3 summarizes the WBCT measurements for PCFD and control groups, demonstrating statistically significant differences across all measurements ($P \leq .0001$). As illustrated in Figure 5, the PCFD group showed higher average values for all measurements on WBCT compared to WBR, reaching statistical significance for HMA, TNC angle, and STI.

Middle Facet Subluxation

The mean MFS percentage was significantly higher in PCFD cases (50.91% ± 35.62%) compared to controls (19.34% ± 9.5%) ($P = .0015$). In the multiple regression analysis involving all 5 radiographic measurements, only TNC angle and HMA were statistically significant predictors of MFS. These variables explained 52.4% of the variability in MFS ($R^2 = 0.5241$) (F ratio = 38.2, $P < .0001$); the remaining 47.6% of MFS variation was not captured by TNC angle and HMA, indicating that almost half of MFS was influenced by other factors beyond these radiographic measurements. The model coefficients showed that a 1-degree increase in TNC angle resulted in a 1.42% increase in MFS ($P < .0001$), whereas a 1-mm increase in HMA resulted in a 1.27% increase ($P = .0093$). Sensitivity analysis comparing regression model using all 73 feet vs only 1 foot per bilateral patient (n = 63) showed virtually identical results ($R^2 = 0.52$ vs 0.54; both $P < .0001$), confirming that bilateral inclusion did not bias the findings.

The bivariate analysis (Figure 6) examined the individual correlations between each WBR parameter and MFS (Table 4). MFS had a moderate positive correlation with TNC angle ($r = 0.68$, 95% CI 0.54-0.79, $P < .0001$), and a weak positive correlation with HMA ($r = 0.39$, 95% CI 0.17-0.56, $P = .0006$).

The partition analysis (Figure 7) identified HMA ≥ 11.4 mm and TNC angle ≥ 38 degrees as categorical

Table 3. Measured Parameters in Weightbearing Computed Tomography for Progressive Collapsing Foot Deformity Cases and Controls.

WBCT parameters	PCFD cases	Controls	*P* Value
Talo-navicular coverage angle, degrees, mean ± SD	47.21 ± 11.51	5.23 ± 4.39	<.0001
Talo–first metatarsal angle, degrees, mean ± SD	−28.72 ± 11.54	−1.50 ± 5.02	<.0001
Hindfoot moment arm, mm, mean ± SD	16.34 ± 6.72	1.9 ± 3.76	<.0001
Sinus tarsi impingement, n (%)			<.0001
Yes	63 (86)	0 (0)	
No	10 (14)	20 (100)	
Middle facet subluxation, percentage, mean ± SD	50.91 ± 35.62	19.34 ± 9.5	.0015

Abbreviations: PCFD, progressive collapsing foot deformity; WBCT, weightbearing computed tomography.

thresholds with complete association to MFS ≥ 18% (G^2 = 31.01 for both). Below these values, cases showed progressively weaker associations. The model's moderate explanatory power (R^2 = 0.273) indicated these thresholds account for only 27.3% of total MFS variability, with the remaining 72.7% suggesting additional contributing factors not captured in this analysis.

Notably, TNC angle and HMA repeatedly emerged as significant predictor across all 3 analytical approaches.

Discussion

This study demonstrates that in PCFD patients, MFS measured on WBCT correlates with TNC angle and HMA measured on WBR. This correlation is particularly relevant where WBCT is unavailable or cost-prohibitive, offering a practical method to assess PTS, a key component of PCFD classification and enhancing the global applicability of the most recent classification system.

These results partially support our hypothesis, as TNC angle, which is used to assess midfoot and forefoot abduction, also showed a connection with MFS, as did HMA, a radiographic hindfoot parameter. These findings demonstrate how all the components of the deformity interact with one another, progressing simultaneously. However, a considerable proportion of the variability in MFS was not explained by these 2 parameters, suggesting the influence of additional factors beyond the radiographic measurements evaluated in this study.

MFS is becoming more recognized as a reliable parameter of PTS in PCFD patients.[1,5,9] MFS exceeding 18% has been suggested as an early threshold for PTS.[9] This finding is especially relevant to our cohort, where 94.5% of PCFD cases demonstrated MFS values above this cutoff. The diagnostic utility of this measurement is supported by the notable difference in mean MFS between our PCFD group (50.91%) and controls (19.34%). Additionally, the clinical relevance extends beyond the diagnosis, as a decrease in MFS after PCFD surgery has been directly associated with improved patient outcomes,[16] positioning it as valuable throughout the entire treatment spectrum, from initial evaluation to postoperative follow-up.

Our results showed consistent directional agreement between WBR and WBCT measurements; however, there were notable quantitative differences. WBCT measurements consistently demonstrated greater values compared to WBR, achieving statistically significant differences for TNC angle, HMA, and STI. These results are consistent with the Shakoor et al[17] study, which also found that WBCT had more severe values than WBR assessment. This consistent trend suggests that WBR measurements underestimate the deformity.

In the multivariate regression model, only TNC angle and HMA were significant radiographic predictors of MFS, together explaining 52.4% of its variability. This relationship reflects the interconnected nature of PCFD components, providing an indirect method to assess MFS through WBR, because progression involves all components simultaneously. Nonetheless, 47.6% of variance remained unexplained, suggesting that factors beyond these radiographic measurements such as soft tissue deficiencies (eg, spring or deltoid ligament incompetence, posterior tibial tendon dysfunction) and dynamic muscle imbalances (eg, peroneal muscles, sural triceps) also contribute to MFS.

We performed a bivariate analysis to evaluate the independent association between each radiographic parameter and MFS and found that TNC angle was the most robust and positively correlated (r = 0.68, 95% CI 0.54-0.79, P < .0001). The characteristic talar malposition in PCFD patients, where the talus plantarflexes and internally rotates, thereby increasing both TNC angle and MFS.[18-20] Although HMA also showed significance, its correlation was weaker (r = 0.39, 95% CI 0.17-0.56, P = .0006). The reason for this limited correlation could be that HMA measures hindfoot valgus without accounting for talar position. Remarkably, our results are consistent with those of Kim et al,[11] who linked the same parameters to late-stage PTS manifestations, specifically, TNC angle with STI and HMA with calcaneofibular bony impingement.[8]

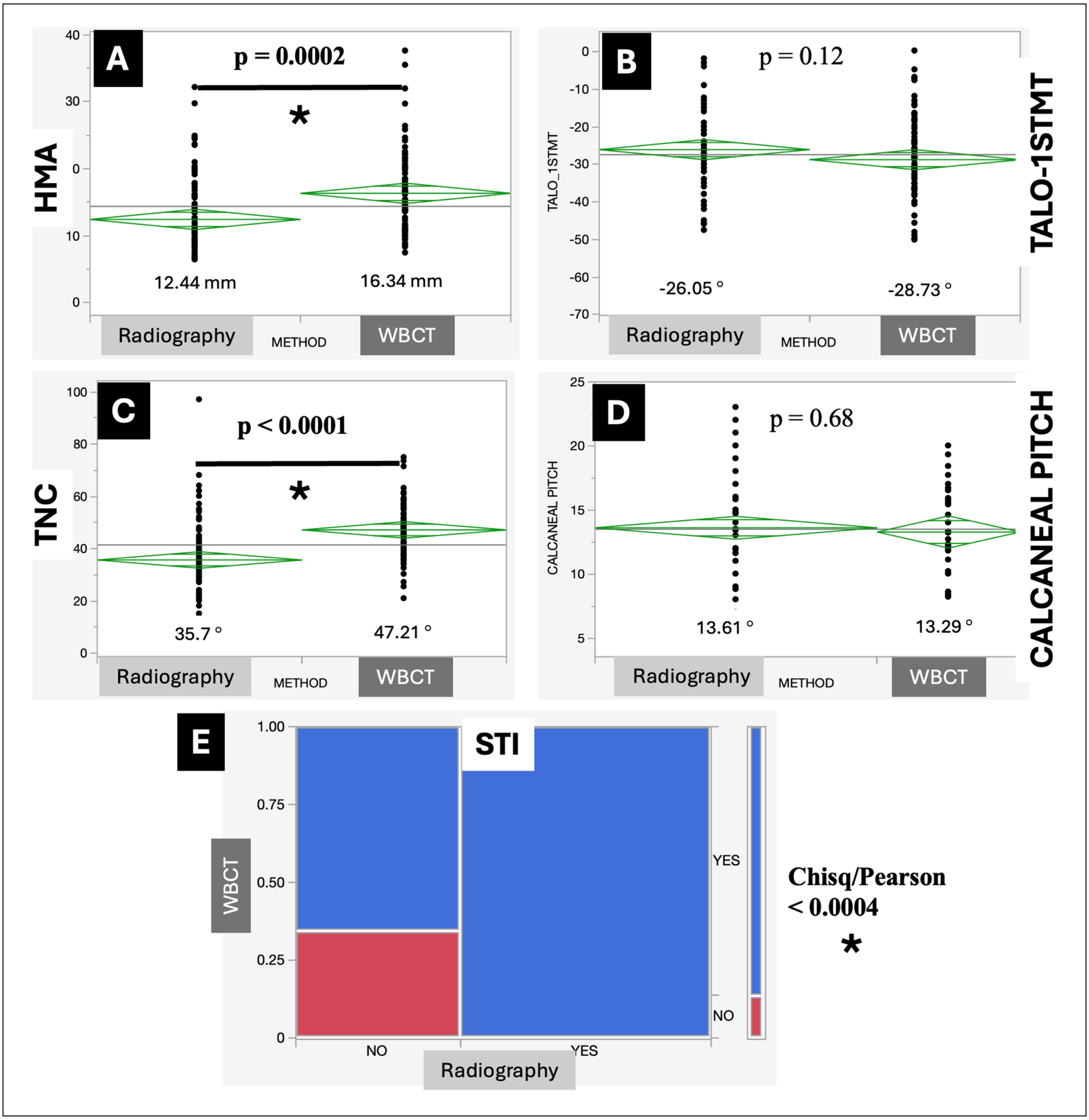

Figure 5. Comparison of average values for parameters obtained from weightbearing radiographic (WBR) and weightbearing computed tomography (WBCT). WBCT yields more severe values for all measurements. Statistically significant differences ($P < .005$) were observed for the hindfoot moment arm (A), the talo–first metatarsal angle (B), talonavicular coverage angle (C), calcaneal inclination angle (D), and sinus tarsi impingement (E) were not statistically significant.

Our partition analysis demonstrated that HMA ≥ 11.4 mm and TNC angle ≥ 38 degrees are critical thresholds for detecting MFS ≥ 18%, with definitive radiographic association ($G^2 = 31.01$), when cases exceed these values. Notably, Kim et al[11] identified higher thresholds for these measurements (HMA ≥ 38.1 mm and TNC angle ≥ 41.2 degrees) to predict lateral bony impingement. Collectively, these data confirm that TNC angle and HMA are the most significant radiographic measurements correlated with PTS; however, their clinical utility appears stage dependent. Although our study identified lower thresholds with moderate predictive power for MFS, Kim et al reported higher thresholds with near-perfect reliability (area under the curve 0.84-0.96, 100% positive predictive value) for lateral

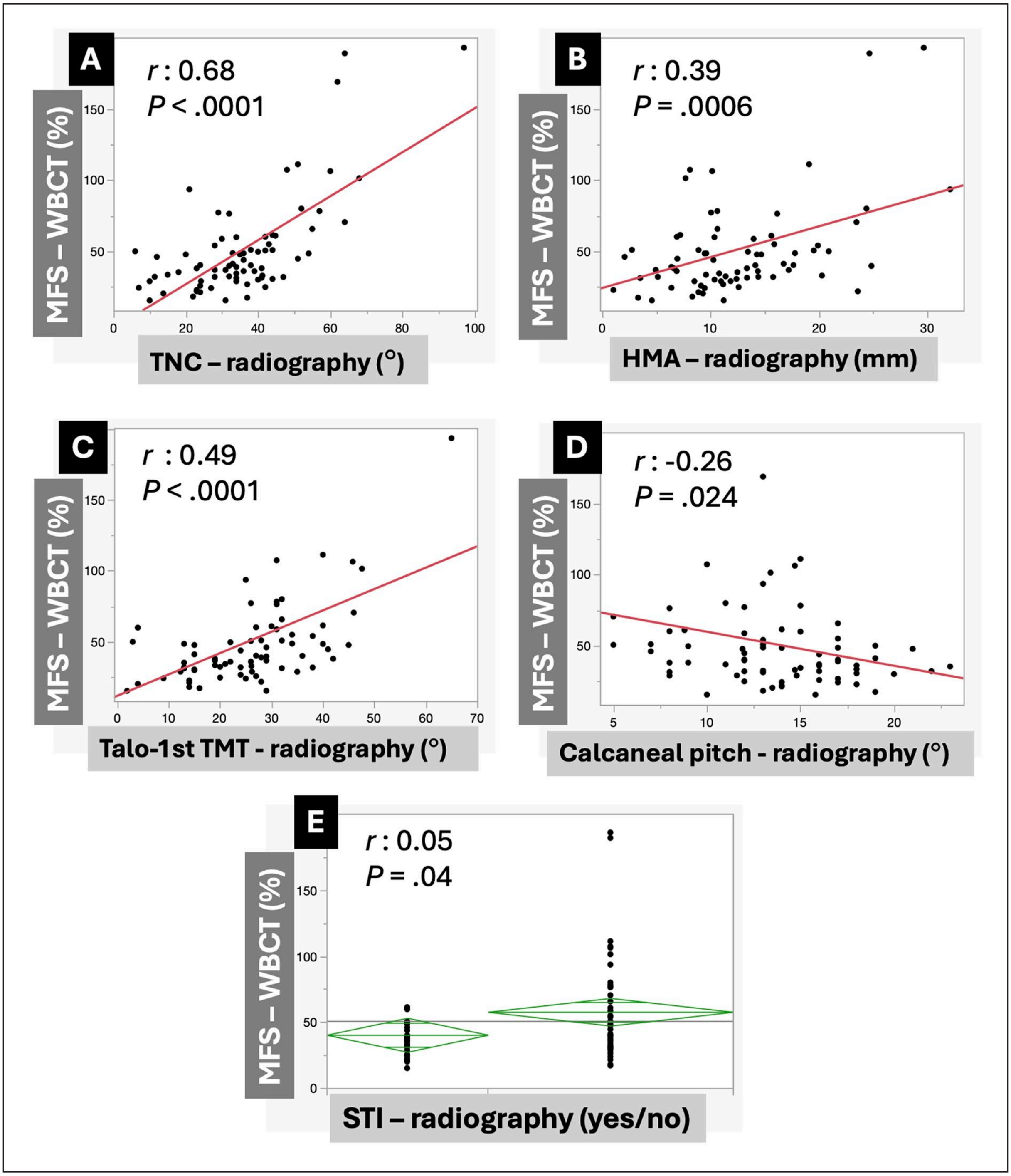

Figure 6. Bivariate analyses between middle facet subluxation and individual weightbearing radiographic parameters. (A) Talonavicular coverage angle. (B) Hindfoot moment arm. (C) Talo–first metatarsal angle. (D) Calcaneal pitch angle. (E) Sinus tarsi impingement. Correlation coefficients *(r)* are shown in each panel.

bony impingement. This divergence suggests TNC angle and HMA are highly specific for advanced PTS, but less sensitive to early subluxation, as evidenced by our model's residual unexplained variability. Therefore, early detection of PTS would be better assessed via WBCT.

Our study attempted to evaluate class D (PTS) through a binary radiographic assessment of STI. However, this approach demonstrated a limited utility, showing a weaker correlation with MFS, significant discrepancy vs the same parameter assessed with WBCT, and the lowest

Table 4. Correlations Between Middle facet subluxation With Weightbearing Conventional Radiographic Parameters.

Radiographic Parameters[a]	Correlation	95% CI	*P* Value
Talo-navicular coverage (TNC) angle[a]	0.68	0.54 to 0.79	<.0001
Hindfoot moment arm (HMA)[a]	0.39	0.17 to 0.56	.0006
Talo-first metatarsal angle[a]	0.49	0.29 to 0.64	<.0001
Calcaneal pitch angle[a]	−0.26	−0.4 to −0.03	.024
Sinus tarsi impingement (STI)[b]	0.05	–	.04

All radiographic measures except STI showed statistically significant correlation with MFS. TNC angle had the strongest correlation, followed by the talo–first metatarsal angle and HMA; all showed positive correlations, increasing in line with worsening MFS. Calcaneal pitch was the only parameter with inverse correlation.
[a]Pearson correlation coefficient.
[b]Point-biserial correlation coefficient.

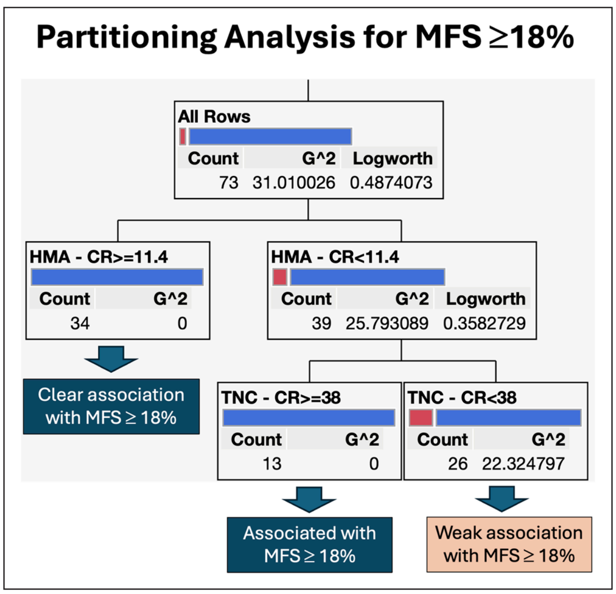

Figure 7. Partition analysis of radiographic parameters for middle facet subluxation (MFS ≥ 18%). Thresholds of hindfoot moment arm (HMA) ≥ 11.4 mm and talonavicular coverage (TNC) angle ≥ 38 degrees showed complete association with MFS ≥ 18% (G^2 = 31.01).

interobserver reliability. These findings question the validity of the lateral-view STI assessment for reliable class D evaluation. Given these constraints in capturing MFS through conventional radiographic parameters we included in this study, it would be worth evaluating alternative radiographic measures like the anteroposterior talocalcaneal (Kite) angle.[21] Though primarily used in pediatric flatfoot,[21,22] its established reliability[23] and the fact that the Kite angle reflects talocalcaneal divergence make it a theoretically promising parameter for MFS assessment. Paradoxically, only 30% of surgeons currently use this measurement to evaluate PCFD.[7]

This study has several limitations to consider. The retrospective design cannot account for the progressive nature of PCFD, which may introduce selection bias because of differing deformity stages at the time of measurement. Although we focused on 4 essential radiographic measurements, others such as the Kite angle could provide additional information about MFS. Incorporating soft tissue evaluation (ligamentous and tendon insufficiency) may provide more comprehensive assessment. Additionally, our control group showed substantial differences in age and BMI compared with the PCFD cohort, unadjusted factors that could influence overall alignment. Finally, as a single-center study, these findings may not be entirely generalized to larger patient populations or clinical practices in other regions.

Conclusion

Our study demonstrates that TNC angle and HMA measured on radiographs correlate with MFS quantified on WBCT. We propose pragmatic thresholds (TNC angle ≥ 38 degrees, HMA ≥ 11.4 mm) to flag possible early PTS when WBCT is unavailable; however, these thresholds account for only a portion of MFS variability and should supplement, not substitute for, WBCT when available. Moving forward, validation of these thresholds in broader, more diverse cohorts and exploration of complementary radiographic measures will be important to improve early detection of peritalar subluxation.

Author Note

This study was performed at Duke Healthcare Orthopedics at Arringdon, Foot and Ankle Division.

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Ethical Approval

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Use of AI Editing Tool During Manuscript Preparation

During the preparation of this work, the authors used Grammarly®: Writing Assistance to review the manuscript for grammatical accuracy and clarity. After using this tool, the authors thoroughly reviewed and edited the content as needed and take full responsibility for the final content of the publication.

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