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The effect of foot structure on 1st metatarsophalangeal joint flexibility and hallucal loading

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ABSTRACT

The purpose of our study was to examine 1st metatarsophalangeal (MTP) joint motion and flexibility and plantar loads in individuals with high, normal and low arch foot structures. Asymptomatic individuals ($n = 61$), with high, normal and low arches participated in this study. Foot structure was quantified using malleolar valgus index (MVI) and arch height index (AHI). First MTP joint flexibility was measured using a specially constructed jig. Peak pressure under the hallux, 1st and 2nd metatarsals during walking was assessed using a pedobarograph. A one-way ANOVA with Bonferroni-adjusted post hoc comparisons was used to assess between-group differences in MVI, AHI, early and late 1st MTP joint flexibility in sitting and standing, peak dorsiflexion (DF), and peak pressure under the hallux, 1st and 2nd metatarsals. Stepwise linear regression was used to identify predictors of hallucal loading. Significant between-group differences were found in MVI ($F_{2,56} = 15.4$, $p < 0.01$), 1st MTP late flexibility in sitting ($F_{2,57} = 3.7$, $p = 0.03$), and standing ($F_{2,57} = 3.7$, $p = 0.03$). Post hoc comparisons demonstrated that 1st MTP late flexibility in sitting was significantly higher in individuals with low arch compared to high arch structure, and that 1st MTP late flexibility in standing was significantly higher in individuals with low arch compared to normal arch structure. Stepwise regression analysis indicated that MVI and 1st MTP joint early flexibility in sitting explain about 20% of the variance in hallucal peak pressure. Our results provide objective evidence indicating that individuals with low arches show increased 1st MTP joint late flexibility compared to individuals with normal arch structure, and that hindfoot alignment and 1st MTP joint flexibility affect hallucal loading.

1. Introduction

Foot structure, characterized by the height of the medial longitudinal arch, has been postulated to play an important role in lower extremity biomechanics and the possible development of musculoskeletal pathology [1,2]. In particular, low arch foot structure has been linked with the development of osteoarthritis (OA) of the 1st metatarsophalangeal (MTP) joint [3,4]. 1st MTP joint OA, also referred to as hallux rigidus, is the most common form of degenerative joint disease in the foot [5]. Radiographic evidence of arthritic changes at the 1st MTP joint have been reported in approximately 46% of women and 32% of men at 60 years of age [6]. Individuals with this disease present with significant pain, reduction in motion and consequent limitations in activities of daily living and quality of life [7]. Specific mechanisms by which foot structure may contribute to the etiology of degenerative changes at the 1st MTP joint remain unclear, however altered joint motion and plantar loading have been identified as two potential pathways by which foot structure may influence the development of 1st MTP joint OA [4,8,9].

Low arch foot structure may alter the orientation of the 1st metatarsal axis, [10] and consequently limit motion at the 1st metatarsophalangeal (1st MTP) joint. Over time, the limitation in joint motion may progress to degenerative OA. Consistent with this theory, a recent epidemiological study found that individuals with low arches (hindfoot valgus) were 23% more likely to subsequently develop 1st MTP joint OA than were those with neutral arches (risk ratio = 1.23; $p < 0.006$) [3]. In contrast, a recent systematic review of case control studies did not find evidence supporting the contention that 1st MTP joint OA is associated with low arch foot structure [11]. While biomechanical theory indicates that foot structure may influence 1st MTP motion, studies examining the

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effect of foot structure on 1st MTP motion and flexibility have reported conflicting results. Differences in methodology and lack of reliable and valid quantitative measurements of foot structure may account for the disagreements in results.

There is growing evidence to suggest that foot structure influences plantar load distribution [1,12,13]. During walking, individuals with high arch foot structure demonstrated increased plantar loads at the lateral forefoot [13], or at the heel and forefoot [1]. Conversely, individuals with low arch foot structure showed higher hallucal loading [12]. Taken together, these studies indicate that foot structure influences plantar loading but its effects on 1st MTP joint and flexibility are less clear.

Independent of foot structure, 1st MTP joint motion and flexibility may have important functional consequences, and has been linked with increased hallucal loading during walking [14]. In patients with 1st MTP joint OA, reduction in 1st MTP joint motion and concomitant increase in hallucal loading has been reported [9,15]. However, in clinical populations, restriction in 1st MTP joint motion and low arch foot structure may co-exist in addition to joint pathology. Consequently, the unique contributions of foot structure and joint flexibility to plantar load distribution cannot be identified from the literature.

Studies assessing 1st MTP joint motion and flexibility and plantar distribution across a range of foot structure in asymptomatic individuals will help identify the independent and combined effects of foot structure and joint motion on plantar load distribution. The purpose of our study was to examine 1st MTP joint motion and flexibility and plantar load distribution in individuals with high, normal and low arch foot structure. We hypothesized that individuals with low arch foot structure would show decreased 1st MTP joint dorsiflexion and increased hallucal loading, compared to individuals with normal and high arch structures.

2. Methods

All procedures were approved by the Institutional Review Board. Informed consent was sought prior to the initiation of study procedures.

2.1. Subjects

Asymptomatic individuals ($n = 61$), with high, normal and low arches, based on resting calcaneal stance position (RCSP,°) and forefoot to rearfoot angle (FF-RF,°) participated in this study [16]. We used Boolean logic to refine Root's original clinical classification, [4] and create three well-separated groups of subjects, and thus eliminated the possibility that a 1° error will result in misclassification of arch height. Our strategy creates three arch height categories with no overlap, and has been previously used to discriminate between low and normal arch foot alignment [16]. Further, recent reports indicate that acceptable intra-tester reliability of forefoot-to-rearfoot position and relaxed calcaneal stance position can be attained using well-defined, standardized measurement methods [17,18]. All subjects were screened for the presence of lower extremity pathology that may influence joint motion and plantar load distribution. A single tester (HJH) obtained measures of RCSP and FF-RF on all subjects. Using a clinically based classification scheme, RCSP and FF-RF values were used to define low, normal and high arch foot structures [4]. Low arch structure was defined as (1) RCSP $\geq 4°$ of valgus, or (2) FF-RF $\geq 5°$ of varus. Normal arch structure was defined as (1) RCSP between 0° and 2° of valgus, and (2) FF-RF between 0° and 4° of varus. High arch structure was defined as (1) RCSP $\geq 0°$ of varus and (2) FF-RF $\geq 1°$ of valgus. A summary of subject characteristics is presented in Table 1.

Table 1
Mean (SD) summary of subject demographics, arch structure, 1st MTP flexibility and plantar loading. Negative values indicate valgus. Significant post hoc differences are denoted by * (Normal vs. Low), $^{\#}$ (Normal vs. High), and $^{+}$ (Low vs. High).

	Low arch	Normal arch	High arch
	n=22	*n*=27	*n*=12
Age (years)	35.6 (11.1)	33.1 (9.9)	42.8 (16.5)
Body mass index (kg/m^2)	22.2 (3.3)	24.4 (4.1)	24.0 (3.6)
Resting calcaneal stance position (°)	−6 (2)$^{*+}$	−1 (1)*	0 (1)$^{+}$
Forefoot to rearfoot angle (°)	7 (5)$^{*,+}$	2 (1)$^{*,\#}$	−2 (1)$^{+,\#}$
Malleolar valgus index (%)	13.7(5.1)$^{*,+}$	7.5 (4.0)*	6.3 (3.3)$^{+}$
Arch height index (%)	0.34 (0.084)	0.36 (0.047)	0.38 (0.031)
Peak pressure (N/cm^2)			
Hallux[a]	41.5 (14.3)	35.1 (17.4)	31.9(13.3)
1st metatarsal[b]	29.0 (16.8)	36.2 (22.8)	33.7 (17.9)
2nd metatarsal[c]	51.3 (18.3)$^{*,+}$	38.7 (13.3)*	36.5 (13.1)$^{+}$

[a] $F_{2,58} = 1.76$, $p = 0.18$.
[b] $F_{2,58} = 0.81$, $p = 0.45$.
[c] $F_{2,58} = 0.54$, $p < 0.01$.

2.2. Procedures

2.2.1. Foot structure

Quantitative measures including malleolar valgus index (MVI), and arch height index (AHI) were used to characterize foot structure. The reliability and validity of these measures has previously been established [14,19].

MVI was measured as previously described [16]. Each subject stood upon a 1 in. thick plexiglas table top overlying a flat bed scanner. An adjustable plexiglas jig was positioned posterior to the calcaneus and used to register the locations of the lateral and medial malleoli. MVI, a measure of static rearfoot alignment, was calculated from a scanned image of the plantar aspect of the subject's foot while in comfortable bilateral stance. The deviation from the midpoint of the transmalleolar axis to the midpoint of the rearfoot, normalized to the foot width in this region comprised the MVI [16].

AHI was measured as described by Williams and McClay [16,19]. AHI was defined as the ratio of dorsum height to truncated foot length (where dorsum height was measured from the floor to the top of the foot at 50% of foot length and truncated foot length was measured from the most posterior portion of the calcaneus to the center of the 1st MTP joint) [19].

2.2.2. 1st MTP motion and flexibility

1st MTP joint flexibility was measured using a specially constructed jig [20]. This device allows the tester to apply a moment about the sagittal axis of the 1st MTP joint with the subject in relaxed, bilateral stance. A single tester (HJH) performed all flexibility testing, and performed three trials on each subject. The resulting angular excursion was measured by a potentiometer while a torque transducer measured the applied moment. The slope of the angle versus moment curves in the first 25% of the joint's range of motion was termed early flexibility (°/N cm), and during the last 25%, late flexibility (°/N cm). Measures of early and late flexibility were obtained in the sitting and standing positions. Intra-rater (between-trial) reliability was established using intraclass correlation coefficients (Model (2,*k*) using statistical software (IBM SPSS v 19, IMB, Somers, NY). Average measure ICC (2,*k*) and 95% confidence intervals of 0.877 (0.837–0.908) and 0.929 (0.906–0.946) were noted for early and late flexibility in sitting, respectively, and 0.945 (0.929–0.958) and 0.883 (0.850–0.910) were noted for early and late flexibility in standing, respectively. Corresponding standard error values were 3.89 and

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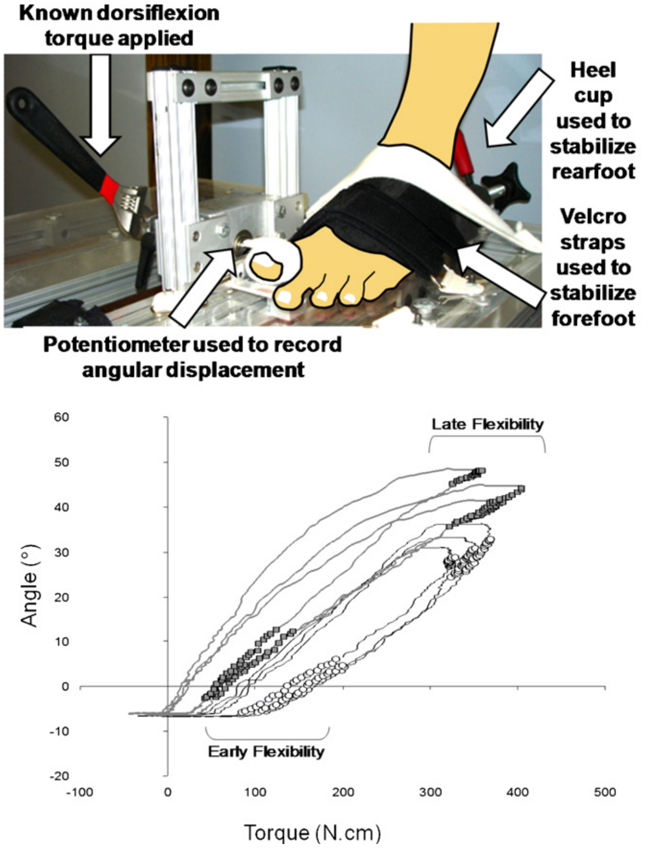

Fig. 1. Device used to record 1st MTP flexibility (top). Representative angle (°, ordinate) versus moment (N cm, abscissa) curve used to calculate 1st MTP joint early and late flexibility in standing (bottom). Circles (black line) depicts a subject with low arch structure, squares (grey line) depicts a subject with high arch structure.

1.52°/N cm for early and late flexibility in sitting, and 1.81 and 2.20°/N cm for early and late flexibility in standing, respectively. A representative angle versus moment curve and a picture of the jig are provided in Fig. 1.

Maximum passive dorsiflexion (DF,°) was recorded using a manual goniometer [21,22]. With the subject supine, the subtalar joint was positioned in neutral, and the ankle dorsiflexed to 90°. The axis of the goniometer was aligned with the center of the 1st MTP joint along the medial aspect of the foot. The stationary arm was aligned with the lateral aspect of the 1st metatarsal, while the moving arm was aligned along the lateral aspect of the proximal phalanx.

2.2.3. *Plantar loading*

Barefoot plantar loading was assessed using a pressure-sensitive plate embedded flush to the surface in the floor (Emed, Novel Inc, St Paul, MN). Data were collected using a mid-gait protocol as subjects walked at self-selected speed [23]. In the mid-gait protocol, plantar pressure data are recorded after a minimum of three steps in order to minimize the effects of acceleration and deceleration associated with gait initiation and termination respectively [24]. Regional plantar loading was assessed using a standard "mask", in the following regions: hallux, 1st and 2nd metatarsals [25]. Plantar loading in each mask was defined using peak pressure (N/cm^2).

2.3. *Data analysis*

A one-way ANOVA with Bonferroni adjusted post hoc comparisons was used to assess between-group differences (normal, high and low arches). Dependent variables included MVI, AHI, early and late 1st MTP joint flexibility in sitting and standing position, peak DF, and peak pressure at the hallux, 1st and 2nd metatarsals.

Correlational analyses were performed using Pearson Moment Product Correlation (r), to determine associations between dependent variables of interest. Linear associations were assessed between foot structure (MVI and AHI) and 1st MTP joint motion and flexibility. Statistical significance (H_o: $\rho = 0$) was assessed using approximate tests based on Fisher's Z transformation ($\alpha < 0.05$).

Foot structure (MVI and AHI) and 1st MTP joint flexibility (early and late 1st MTP flexibility in sitting and standing) and peak DF were entered into a stepwise linear regression to identify the strongest subset of hallucal loading predictors. The criteria used for entering independent predictors were as follows: at each step, the independent variable not in the equation that has the smallest probability of F was entered, if that probability was <0.05. Variables already in the regression equation were removed if their probability of F was >0.10. The method terminated when no more variables are eligible for inclusion or removal. In addition, adjusted R squared values were examined to assess the proportion of variance in the dependent variable explained by the independent variables, while accounting for multiple independent variables.

3. Results

3.1. *Between-group differences in foot structure, 1st MTP joint motion and flexibility, and plantar pressure*

Significant between-group differences were found in MVI ($F_{2,56} = 15.4$, $p < 0.01$). No between-group differences were found for AHI ($F_{2,55} = 1.3$, $p = 0.28$). Results and post hoc comparisons are summarized in Table 1.

Significant between-group differences were noted for 1st MTP late flexibility in sitting ($F_{2,57} = 3.7$, $p = 0.03$), and standing ($F_{2,57} = 3.7$, $p = 0.03$). Post hoc comparisons demonstrated that 1st MTP late flexibility in sitting was significantly higher in individuals with low arch compared to high arch structure, and that 1st MTP late flexibility in standing was significantly higher in individuals with low arch compared to normal arch structure (Table 1). No between-group differences were found in peak DF ($F_{2,58} = 0.64$, $p = 0.53$), 1st MTP early flexibility in sitting ($F_{2,57} = 0.11$, $p = 0.90$), and 1st MTP early flexibility in standing ($F_{2,57} = 1.2$, $p = 0.28$).

A significant effect of foot structure on peak pressure was noted for the 2nd metatarsal ($F_{2,58} = 0.54$, $p < 0.01$, Table 1). Post hoc comparisons indicated that individuals with low arch structure sustained significantly higher 2nd metatarsal peak pressure compared to individuals with high or normal arch structure (Table 1) (Fig. 2).

3.2. *Association between 1st MTP joint motion and flexibility and foot structure*

Late flexibility of the 1st MTP joint was positively related to MVI ($r = 0.27$, $p = 0.02$, Fig. 3). Late flexibility of the 1st MTP joint sitting and standing was negatively related to AHI ($r = -0.29$, $p = 0.02$ and $r = -0.25$, $p = 0.03$ respectively, Fig. 3).

3.3. *Association between 1st MTP joint motion and flexibility and plantar loading*

Results from stepwise linear regression indicate that foot structure (MVI) and early 1st MTP joint flexibility in sitting serve as significant predictors of hallucal peak pressure. The results of

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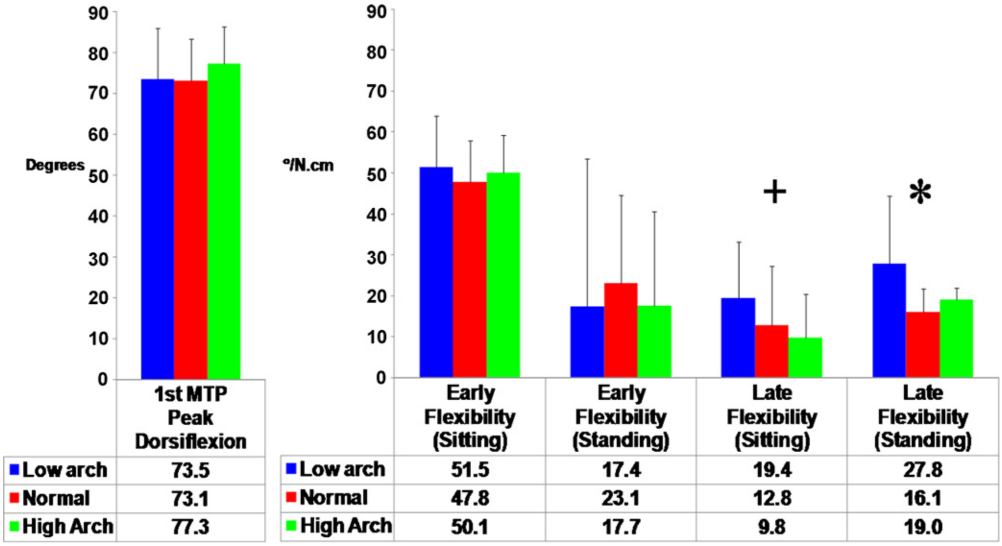

Fig. 2. Summary of average 1st MTP joint dorsiflexion and flexibility. Error bars indicate standard deviation. Significant post hoc differences are denoted by * (Normal vs. Low), # (Normal vs. High), and + (Low vs. High).

stepwise linear regression yielded the equation below and are summarized in Table 2.

$$\text{hallucal peak pressure} = 31.85 + (1.33 \times \text{MVI}) + (-0.162 \times \text{1st MTP early flexibility in sitting})$$

4. Discussion

The unique findings of this study provide objective evidence confirming the effect of arch structure on 1st MTP joint motion and flexibility. Individuals with low arches demonstrated increased 1st MTP joint late flexibility during standing compared to individuals with normal arch structure. Consistent with this finding, we found that increasing MVI (low arch foot structure) was weakly related to 1st MTP joint late flexibility during standing. Our results also support the contention that foot structure and 1st MTP joint flexibility affect regional plantar loading. Stepwise regression analysis indicated that foot structure (MVI) and 1st MTP joint early flexibility in sitting explain about 20% of the variance in peak pressure sustained under the great toe.

Our study sample included asymptomatic individuals with a wide range of foot structures, reflected in their rearfoot-to-tibia and forefoot-to-rearfoot alignment (Table 1). In terms of MVI, our findings are consistent with values reported previously in the literature [16,26,27]. Song et al. reported a mean (SD) MVI of 17.9 (4.3) and 7.3 (3.7) in planus and rectus feet respectively, while other studies have reported mean values of 10.3–9.5 in rectus feet [26,27]. Mean (SD) AHI in our study is consistent with 0.340 (0.030), 0.316 (0.027) and 0.339 (0.027) reported by Butler et al. [14], Williams and McClay [19], and Teyhan et al. [13] respectively. Reliability is a primary concern when assessing static foot alignment using conventional clinical measurements, therefore, we used measurements with previously established intra-tester reliability [17,18]. Our philosophy of classifying feet uses Boolean logic to create well-separated categories based on Root's original classification. The validity of the classification approach has been established in previous work using discriminant analysis [16]. Additional studies are needed comparing our classification approach to alternatives protocols [28] and against a clinical or radiographic gold standard used to defined arch height.

Several investigations have assessed peak dorsiflexion of the 1st MTP joint under active and passive conditions [21,22,29] and have reported values ranging from 40 to 110°. Differences in criteria for determining end range of motion and natural variations in ranges of motion among different study samples may account for the variability between reported values. Our findings indicate a modest decrease in peak dorsiflexion (~4°, effect size = 0.40) in individuals with low arch structure compared to those with high arch structure. These results are consistent with the theory that low arch foot structure may alter the orientation of the 1st metatarsal axis, and consequently limit motion at the 1st MTP joint [10]. We used an instrumented jig to quantify flexibility of the 1st MTP joint during relaxed bilateral weight bearing stance [20]. Low arch subjects also showed increased late flexibility in sitting and standing. The increased 1st MTP joint flexibility may suggest that

Table 2
Adjusted *R* square (top) and regression coefficients (bottom) from linear regression analysis to identify predictors of hallucal peak pressure.

Model	*R*	*R* square	Adjusted *R* square	Std. error of the estimate	Change statistics				
					R square change	*F* change	df1	df2	Sig. *F* change
Hallux peak pressure[a]	.47	.22	.19	14.1	.07	5.49	1	54	.023

Model	Unstandardized coefficients		Standardized coefficients	*t*	Sig.
	B	Std. error	Beta		
(Constant)	31.85	4.83		6.59	.000
MVI	1.32	.37	.43	3.52	.001
1st MTP early flexibility (sitting)	−.16	.06	−.28	−2.34	.023

[a] Predictors: (Constant), MVI, 1st MTP early flexibility in sitting.

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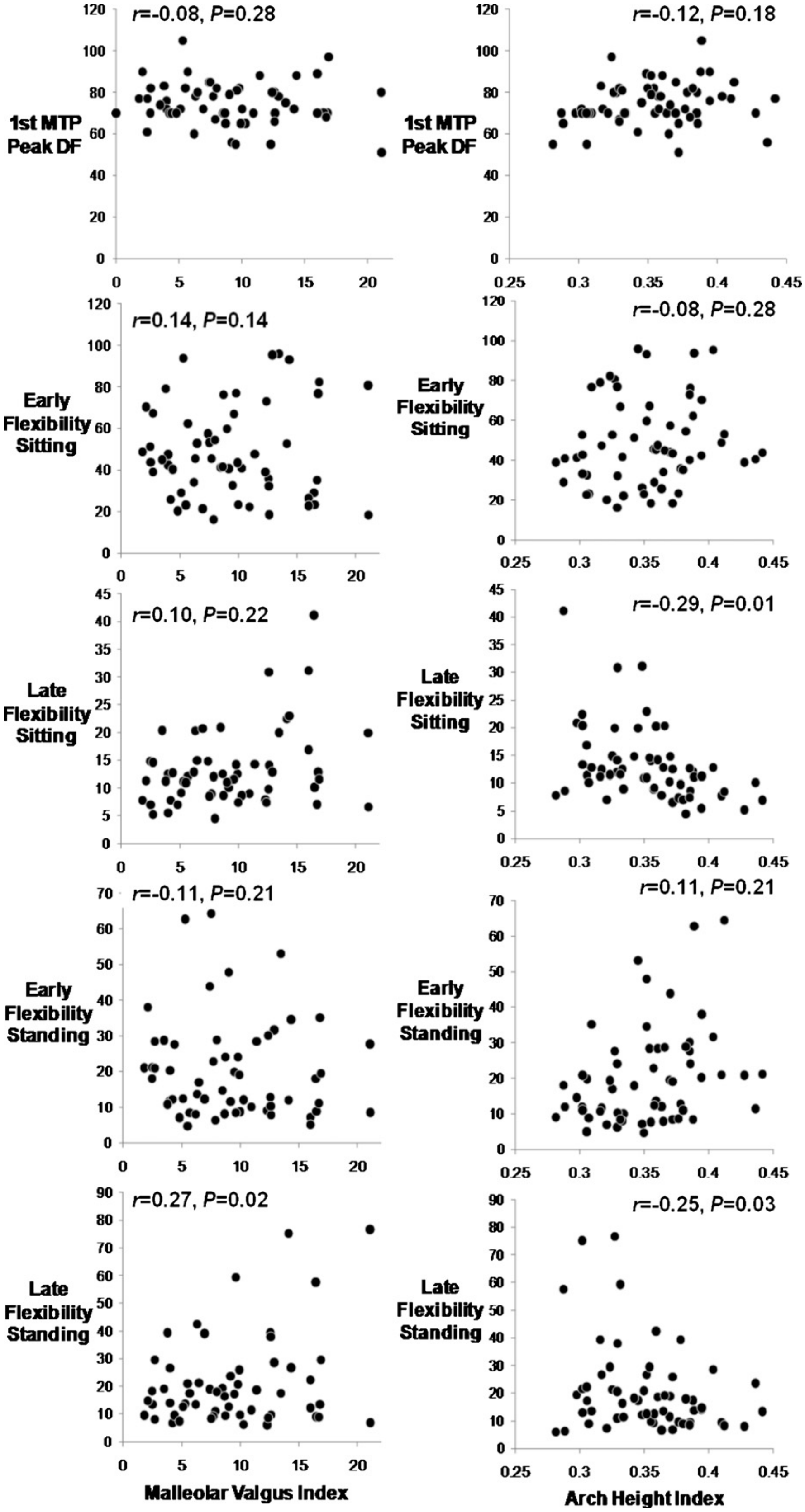

Fig. 3. Scatter plots depicting the relationship between arch height index and 1st MTP joint dorsiflexion ($r = -0.12$, $P = 0.18$), early flexibility in sitting ($r = -0.08$, $P = 0.28$), early flexibility in standing ($r = 0.11$, $P = 0.21$), late flexibility in sitting ($r = -0.29$, $P = 0.01$) and late flexibility in standing ($r = -0.25$, $P = 0.03$) are presented in the right column. Scatter plots in the left column depict the relationship between malleolar valgus index and 1st MTP joint dorsiflexion ($r = -0.08$, $P = 0.28$), early flexibility in sitting ($r = 0.14$, $P = 0.14$), early flexibility in standing ($r = -0.11$, $P = 0.21$), late flexibility in sitting ($r = 0.10$, $P = 0.22$) and late flexibility in standing ($r = 0.27$, $P = 0.02$). Arch height index and malleolar valgus index are ratios, and therefore not expressed in absolute units, 1st MTP dorsiflexion is expressed in°, flexibility is expressed in N/cm.

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the articulations of the foot are in a loose-packed position in individuals with low arch foot structure, consistent with the biomechanical impression that a low arch foot may be less rigid [30]. Correlational analysis indicated the presence of linear relationships between measures of foot structure (MVI, AHI) and late flexibility of the 1st MTP joint in sitting and standing. However, these relationships, while statistically significant, accounted for a small portion of overall variance (∼10%), indicating that arch structure may play a small role in 1st MTP joint flexibility in asymptomatic feet. Additional studies are indicated in individuals with foot pathology such as 1st MTP joint OA.

Increasing evidence supports the notion that plantar loading and consequent development of symptoms may be affected by multiple factors, chief among which are foot structure, 1st MTP joint flexibility and the presence of pathology [9,13,15,29,31,32]. The elevated 2nd metatarsal head plantar loading demonstrated by individuals with low arch structure (Table 1) may be indicative of first ray hypermobility [33]. Individuals with low arch foot structure also showed trends towards higher hallucal loading (30% increase hallucal pressure in low arch foot structure compared to high arch, effect size = 0.74). To investigate the individual and combined role of arch structure and 1st MTP joint flexibility on hallucal loading in asymptomatic subjects, we applied a stepwise regression model. Our findings indicate that a model including foot structure (MVI) and 1st MTP early flexibility in sitting was able to explain approximately 20% of the variance in hallucal loading. These findings support the contention that hindfoot alignment may influence hallucal loading [3]. Contrary to our expectation, peak 1st MTP dorsiflexion was not identified as a significant predictor of hallucal loading in asymptomatic subjects. Peak 1st MTP motion has been identified as a key predictor of hallucal loading in patients with diabetes and peripheral neuropathy [29,34] and in patients with 1st MTP joint OA [9,15]. In addition, the presence of deformities such as hammer toe and hallux valgus have also been identified as significant contributors to hallucal loading in patients with diabetes mellitus and peripheral neuropathy [29,32]. Future studies addressing the role of arch structure and 1st MTP joint flexibility are indicated in clinical populations such as in patients with 1st MTP joint OA.

In summary, we assessed 1st MTP joint motion and flexibility and hallucal loading in asymptomatic individuals with high, low and normal arch structures, using clinically relevant measures with robust reliability and validity. Individuals with low arches demonstrated increased 1st MTP joint late flexibility during standing compared to individuals with normal arch structure. Stepwise regression analysis indicated that foot structure (MVI) and 1st MTP joint early flexibility in sitting explain about 20% of the variance in peak pressure sustained under the great toe. Additional studies are needed to assess the kinematic consequences of differences in arch structure and 1st MTP joint function during weight-bearing activities of daily living such as walking. Future investigations should also evaluate the effect of foot structure and 1st MTP joint function on plantar loading in clinical populations such as individuals with 1st MTP joint OA.

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Conflict of interest statement

We, the authors, affirm that we have no financial affiliation (including research funding) or involvement with any commercial organization that has a direct financial interest in any matter included in this manuscript, except as disclosed in an attachment and cited in the manuscript.

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