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Foot Type Biomechanics Part 1: Structure and Function of the Asymptomatic Foot

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Abstract

Background—Differences in foot structure are thought to be associated with differences in foot function during movement. Many foot pathologies are of a biomechanical nature and often associated with foot type. Fundamental to the understanding of foot pathomechanics is the question: do different foot types have distinctly different structure and function?

Aim—To determine if objective measures of foot structure and function differ between planus, rectus and cavus foot types in asymptomatic individuals.

Methods—Sixty-one asymptomatic healthy adults between 18 and 77 years old, that had the same foot type bilaterally (44 planus feet, 54 rectus feet, and 24 cavus feet), were recruited. Structural and functional measurements were taken using custom equipment, an emed-x plantar pressure measuring device, a GaitMatII gait pattern measurement system, and a goniometer.

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Conflict of Interest Statement
None

Generalized Estimation Equation modeling was employed to determine if each dependent variable of foot structure and function was significantly different across foot type while accounting for potential dependencies between sides. Post hoc testing was performed to assess pairwise comparisons.

Results—Several measures of foot structure (malleolar valgus index and arch height index) were significantly different between foot types. Gait pattern parameters were invariant across foot types. Peak pressure, maximum force, pressure-time-integral, force-time-integral and contact area were significantly different in several medial forefoot and arch locations between foot types. Planus feet exhibited significantly different center of pressure excursion indices compared to rectus and cavus feet.

Conclusions—Planus, rectus and cavus feet exhibited significantly different measures of foot structure and function.

1. Introduction

Differences in foot structure are postulated to be associated with differences in foot function during static posture or dynamic movement. Many foot pathologies are biomechanical in origin and often associated with foot type [1-4]. Foot type is a clinical concept that aims to simplify the anatomical complexities of the human foot (28 bones, 33 joints, 112 ligaments, controlled by 13 extrinsic and 21 intrinsic muscles). As described in 1977 by Root, Orien, and Weed, clinicians can determine an individual's foot type by goniometric measurements of hindfoot and forefoot alignments [5]. Foot type categorizes feet as planus (low arched with a valgus hindfoot and/or varus forefoot), rectus (well aligned hindfoot and forefoot), and cavus (high arched with a varus hindfoot and/or valgus forefoot) [5]. Planus feet generally over-pronate, causing the ground reaction forces (GRF) to move medially throughout the stance phase of gait, while cavus feet generally over-supinate, making the GRF move laterally throughout stance. Planus feet are associated with hallux valgus, hallux limitus and rigidus, and posterior tibial tendon dysfunction [1]. Furthermore, planus feet are considered a risk factor in the development of overuse injuries [4, 6], while cavus feet are associated with hammertoes and claw toe deformities [3, 7]. Rectus feet have not been directly associated with pathology or injury in the literature.

It is not clear why certain foot pathologies are associated with specific foot types or why some individuals with non-rectus foot types are asymptomatic. In order to systematically study foot pathologies, responses to treatment, and methods of prevention, objective measures of foot structure and function that differ between foot types are needed.

The purpose of this study was to determine if objective measures of foot structure and function are different for planus, rectus and cavus feet in asymptomatic individuals. Two hypotheses were formed: (1) measures of foot structure (malleolar valgus index, arch height indices, and arch height flexibility) will be different across foot types and (2) measures of foot function (center of pressure excursion index, peak pressure, maximum force, pressure-time-integral, force-time-integral, and contact area) will be different across foot types. Foot type will serve as the independent variable while foot structure and function are the dependent variables.

2. Methods

All procedures were approved by the Institutional Review Board. All enrolled individuals signed a consent form and were provided minimal compensation for expenses. Testing was performed within the motion analysis laboratory.

2.1 Subject Recruitment

Sixty-one asymptomatic healthy adults, that had the same foot type bilaterally, were recruited for enrollment into this investigation. Subjects were between 18 and 77 years old, had no current symptoms of pain, had no foot or ankle pathology, and were able to ambulate independently. Individuals with neuromusculoskeletal disease, uncontrolled cardiovascular disease, or lower extremity surgery within the past year were excluded. Each foot of each participant was categorized by clinical exam into a foot type group: planus, rectus or cavus. Resting calcaneal stance position (RCSP) and forefoot to rearfoot relationship (FF-RF) based criteria were used to classify foot types [5]:

- planus: RCSP 4° valgus OR FF-RF 4° varus
- rectus: 0° RCSP 2° valgus AND 0° FF-RF 4° varus
- cavus: RCSP 0° varus AND FF-RF 1° valgus

RCSP and FF-RF were measured with a 1° resolution goniometer.

2.2 Measures of Foot Structure

Each measurement was taken once per foot. To avoid the issue of inter-rater reliability one rater (HJH) measured all foot structure parameters.

Malleolar valgus index, MVI (%), is a measure of standing hind foot alignment (Fig.1a) [8]. MVI is the deviation of the transmalleolar midpoint relative to the longitudinal foot bisection, normalized to ankle width.

Arch height index, AHI (%), is a measure of the dorsal arch height normalized to foot length (Fig 1b). Maximum foot length, truncated foot length (heel to 1st metatarsophalangeal joint), and arch height at one half of foot length were measured on each foot while standing. AHI was calculated as the ratio of arch height to truncated foot length expressed as a percent in both sitting and standing postures [9].

Arch height flexibility, AHF (mm/kN), is a measure of the change in arch height between sitting and standing conditions, normalized to change in load, estimated to be 40% of body weight.[9] AHF was calculated as follows:

$$AHF = \frac{(AH_{standing} - AH_{sitting})}{0.4 * BW} \times 100 \quad (1)$$

2.3 Measures of Foot Function

Foot function incorporated plantar loading and gait pattern parameters. Five acceptable trials per foot were collected for each measure while subjects walked at their self-selected speed. The means of the five trials were used for statistical analysis.

Plantar Loading Parameters—Each individual walked across an emed-x (Novel, Munich, Germany) plantar pressure measuring device (1.6% full-scale error) [10, 11], which collected dynamic loading data using a mid-gait protocol. The following plantar parameters were calculated from the maximum pressure plot (Fig. 1c).

Center of pressure excursion index, CPEI (%), is a measure of dynamic foot function. It is the concavity of the center of pressure curve in the metatarsal head region, normalized to foot width [8].

A twelve segment mask (scalable geometry-based algorithm) was used to calculate the following parameters in each anatomical plantar region (Fig. 1d) [12].

Peak pressure, PP, was calculated as absolute values (N/cm^2) and normalized by PP beneath the entire foot (total PP).

Maximum force, MF, was calculated as absolute values (N) and normalized by total MF.

Pressure-time integral, PTI, was calculated as absolute values ($\text{N}\cdot\text{s}/\text{cm}^2$) and normalized by total PTI.

Force-time integral FTI, was calculated as absolute values ($\text{N}\cdot\text{s}$) and normalized by total FTI.

Area was calculated as absolute values (cm^2) and normalized by total area.

Gait Pattern Parameters—Each participant walked across a 7.32m GaitMatII system (EQ, Inc, Chalfont, PA, USA) to record the following:

Stride length was calculated as absolute values (m) and normalized by stature.

Step length was calculated as absolute values (m) and normalized by stature.

Stance and *swing times* were calculated as absolute values (s).

Double support time was calculated as absolute values (s) and normalized by gait cycle time.

Gait cycle time was calculated as absolute values (s) and normalized by gait cycle time.

Cadence (steps/min) and *speed* (m/s) were averaged over the entire trial.

2.4. Statistical Analysis

The hypotheses were formulated to assess if foot structure (MVI, $\text{AHI}_{\text{sitting}}$, $\text{AHI}_{\text{standing}}$, AHF) and foot function (plantar loading and gait pattern parameters) were significantly different across foot type (planus, rectus, and cavus). All descriptive and comparative statistical analysis was performed using SPSS software (IBM, Chicago, IL, USA). Generalized Estimation Equation (GEE) modeling was employed with a linear identity link function to determine if each dependent variable of foot structure and function was significantly different across foot type. The GEE model permitted the inclusion of bilateral data (122 feet) by accounting for the covariance between potentially dependent measures (right and left feet). The general Chi-square (χ^2) was calculated for each dependent variable with significance set at $p < 0.05$. If significant, a standard least significant difference (LSD) post hoc test was performed with Bonferroni correction ($p < 0.0167$) to account for multiple comparisons between the three foot types.

3. Results

3.1 Test subject demographics

Sixty-one test subjects were enrolled in this study with the following characteristics:

- planus - 22 subjects, 44 feet, 12 females, height = 1.7 ± 0.1 m, weight = 675.4 ± 146.9 N, BMI = 23.3 ± 4.3 kg/m^2 , age = 35.6 ± 11.0 years
- rectus - 27 subjects, 54 feet, 19 females, height = 1.7 ± 0.1 m, weight = 662.6 ± 138.7 N, BMI = 24.4 ± 4.1 kg/m^2 , age = 33.1 ± 9.8 years

- cavus - 12 subjects, 24 feet, 6 female, height = 1.7 ± 0.1 m, weight = 720.8 ± 155.0 N, BMI = 24.0 ± 3.5 kg/m², age = 42.8 ± 16.2 years

The subjects in each group had similar characteristics with the exception that individuals with cavus feet were 7-9 years older than those with rectus and planus feet ($p=0.004$).

3.2 Measures of Foot Structure

MVI, AHI_{sitting}, and AHI_{standing} were significantly different across foot type (Table Ia). Post hoc analysis revealed that AHI_{sitting} and AHI_{standing} parameters were significantly different between planus, rectus, and cavus feet. Also, MVI distinguished planus from rectus and cavus foot types. There were no significant differences in AHF across foot types.

3.3 Measures of Foot Function

Table Ib shows the absolute gait pattern parameter values were invariant across foot types. When normalized by gait cycle time, double support and stance times were significantly different across foot type. Post hoc analysis revealed a statistically significant difference between planus and cavus feet for both parameters. The minimum clinically important difference (MCID) has been set at 15% by the investigators and none of the normalized gait pattern parameters exceed this threshold.

Peak pressure distribution across foot types is shown in Figure 2. CPEI, PP, and MF parameters are summarized in Tables IIa and IIb. The following parameters were found to be significantly different across foot types: CPEI, hallucal peak pressure (PP-hallux), normalized PP-hallux, PP-toe2, PP-metatarsal head (MH) 2, normalized PPMH2, MF-hallux, normalized MF-hallux, MF-toe2, normalized MF-toe2, normalized MF-MH1, normalized MF-MH5, MF-medial arch, and normalized MF-medial arch. The post hoc analyses for each significant parameter are shown in Tables IIa-b.

PTI, FTI and area parameters are summarized for each masked region in Tables IIIa-c. The following parameters were significantly different across foot types: PTI-hallux, normalized PTI-MH5, normalized PTI-medial arch, FTI-hallux, normalized FTI-hallux, FTI-MH4, normalized FTI-MH5, FTI-medial arch, area-toe2, normalized area-MH4, area-MH5, normalized area-MH5, area-medial arch, and normalized area-medial arch. The post hoc analyses for each significant parameter are shown in Tables IIIa-c.

4. Discussion

4.1 Why study foot types?

Given that individuals with excessive pronation (planus) or supination (cavus) tend to be more vulnerable to certain pathologies, an understanding of the biomechanics associated with different foot types is warranted [13]. In military and athletic populations, cavus and planus foot types are associated with increased risk of tibial stress injuries as compared to rectus foot type [6, 14]. Individuals with diabetes and peripheral polyneuropathy are at risk for developing neuropathic foot ulcers. Diabetic patients with planus feet tend to ulcerate in the medial forefoot, while those with cavus feet ulcerate in the lateral forefoot [15]. This study was conducted 1) to reveal the structural and functional differences in asymptomatic individuals with planus, rectus, and cavus foot types and 2) to serve as a basis for future pathomechanical investigations.

4.2 Foot type recruitment

Based on our cohort, the prevalence of each foot type may not be equal among the general population. The greater percentage of planus (36%) and rectus feet (44%) in this study may

reflect the higher prevalence of these foot types in the asymptomatic population; cavus feet (20%) were relatively rare and therefore most difficult to recruit. In a study of 398 individuals with diabetes, 51.5% were rectus, 29% were planus and 19.5% were cavus.[13] While our findings were similar, it is not clear whether foot type prevalence associated with other pathologies may be different than that of asymptomatic healthy individuals.

4.3 Foot Structure

Several structural parameters (MVI, AHI_{sitting} , and AHI_{standing}) were sensitive to foot type. Both AHI_{sitting} and AHI_{standing} parameters distinguished planus, rectus and cavus feet. These parameters were obtained using a simple and reliable mechanical device [16]. Although there were no differences across foot types, AHF was clinically interesting. Flexible pathologic feet may be treated with foot orthoses, but rigid feet may require surgical reconstruction. From this data, AHF was not a function of foot type and there was an equal likelihood of having a flexible or stiff arch for planus, rectus, or cavus feet.

MVI could distinguish planus from rectus and cavus feet. This result corroborates the findings of Song et al. where asymptomatic planus and rectus feet exhibited a significant difference in hindfoot alignment [8]; however, MVI could not discriminate between cavus and rectus feet. This was expected because MVI is conceptually like RCSP, which was not different between asymptomatic cavus and rectus feet. In severely inverted pathologic cavus feet, RCSP and MVI may be different than in healthy rectus and cavus feet. Although MVI measurements require specialized equipment and software they have demonstrated high reliability in a previous investigation [8].

In light of this information, the first hypothesis, measures of foot structure (MVI , AHI_{sitting} , AHI_{standing} , and AHF) will be different across foot types, was accepted.

4.4 Foot function

None of the temporal-spatial parameters during gait were significantly different across foot type. Normalized stance and double support times were statistically, but not clinically, significantly different. Hence, gait pattern was invariant to foot type.

The following functional parameters were sensitive to foot type: CPEI, PP, MF, PTI, FTI, and area. In other studies, functional measures (CPEI, PP, MF) have demonstrated excellent test-retest and between-day reliability [8, 17]. Our data show some foot function parameters with substantial variability (Tables III and IV). This may be due to the inherent anatomical complexity of the foot and the lack of precise control humans have over its biomechanical behavior. This was accounted for by averaging each functional variable over 5 trials.

Most differences in foot function were found between planus and cavus feet. One exception was CPEI, where planus feet were described by lower CPEI values (indicating a less concave COP trajectory and medially directed GRF) compared to both rectus and cavus feet. Rectus and cavus feet could not be separated using CPEI. This may have resulted from excluding pathologic cavus feet which display a more severe concave and lateral COP trajectory than rectus and asymptomatic cavus feet.

For plantar loading parameters, planus feet had higher medial pressures and forces than cavus feet. This was expected because of the difference in COP trajectory between these two foot types.

Many individuals with planus feet can have excessive dorsal translation of the first ray (i.e. medial cuneiform, 1st metatarsal, and hallux) [18]. This phenomenon, referred to as a 'hypermobile first ray', is supported by the findings that planus feet had lower loads in MH1

than MH2. As an individual with planus feet and a hypermobile 1st ray walks, the 1st metatarsal elevates during stance, leaving MH2 to bear a larger load. These data suggest that 1st ray hypermobility may be present in individuals with planus feet, even if they are asymptomatic. Although 1st ray mobility was not directly measured in this study, 1st ray hypermobility in planus feet was expected, given the degree of forefoot varus alignment.

In this study of asymptomatic individuals, peak load and load-time parameters were higher in planus and cavus feet compared with rectus feet. Thus, foot type should be considered as a covariate in studies of pathologic feet. For example, in a diabetic population, the combination of foot type and loading parameters may be important factors in the development of plantar ulceration.

Based on this information, the second hypothesis, measures of foot function will be different across foot types, was accepted for plantar loading but not for gait pattern parameters.

4.5 Future work

Future studies are needed to evaluate the effect of foot type, structure, and function on foot pathologies, such as osteoarthritis and diabetes, in comparison to this normative data set to better understand their origin and progression. These tools may also be used to evaluate and develop conservative and surgical treatments to alleviate symptoms and improve foot function through basic modifications of foot structure.

4.6 Limitations

The unequal number of subjects in subgroups (primarily a result of fewer cavus feet) is a potential limitation as it may lead to unequal group variances. However, the variances in this study were not different for the vast majority of parameters.

4.7 Significance

This is the first study to identify structural and functional parameters that are able to distinguish planus, rectus, and cavus foot types in asymptomatic individuals spanning a wide age range. Furthermore, these measures are noninvasive and do not require ionizing radiation to distinguish planus, rectus, and cavus feet. Foot structure parameters can be cost-effectively measured within a clinician's office with basic instrumentation. Plantar loading parameters require a plantar pressure measuring device although there are several commercially-available systems which could be used in a clinician's office.

Summary

A study of healthy asymptomatic individuals with *planus*, *rectus*, and *cavus* feet was conducted to determine if foot structure and function were sensitive to foot type. Several reliable measures of foot structure and function differed across foot type. Hindfoot alignment, as measured by MVI, was significantly larger in planus feet compared with rectus and cavus feet. AHI, sitting or standing, was able to distinguish each foot type. Gait pattern parameters were invariant to foot type. Dynamic pronation, as measured by CPEI, demonstrated lower values for planus compared to either rectus or cavus feet. Additional measures of foot function (PP, MF, PTI, FTI, and area) had significant differences across foot types. The architecture of the foot plays a major role in directing the magnitude of load from body weight through different pedal structures.

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Study Information.

This study was approved by the Institutional Review Board at the Hospital for Special Surgery.

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Highlights I

- We investigated the structure and function of different foot types.
- 61 healthy individuals with 44 planus, 54 rectus, and 24 cavus feet were recruited.
- Measures of foot structure and function were different across foot types.
- Gait pattern parameters were invariant across foot types.
- Foot type should be used as a covariate in studies of lower extremity function.

Figure 1.

a.) Malleolar valgus index (MVI) parameters being measured, using a custom instrument. MVI is the deviation of the transmalleolar midpoint relative to the longitudinal foot bisection, normalized to ankle width. b.) Arch height index (AHI) being measured, using a custom instrument. AHI is a measure of the dorsal arch height normalized to truncated foot length. c.) Plantar pressure distribution showing the center of pressure excursion index (CPEI) - the concavity of the center of pressure curve in the metatarsal head region, normalized to foot width. d.) A twelve segment mask, developed using Novel software, to permit automated calculations of peak pressure in each anatomical plantar region.

Peak Pressure Measurements by Foot Type

Figure 2.
Peak pressure measurements across foot types in each of the 12 anatomical plantar regions.
Significant differences are denoted by an '*'.
* p < 0.05

Result Summary for Foot Structure and Gait Pattern Parameters across Foot Type for Asymptomatic Test Subjects

Table I

Table Ia: Foot Structure		Planus		Rectus		Cavus		GEE Results		Post-hoc Analysis (p-values)		
		Mean	SD	Mean	SD	Mean	SD	χ^2	p-value	P v C	P v R	R v C
MVI (%)		13.34	5.37	7.40	3.88	6.73	3.52	17.23	0.000	0.000	0.000	0.457
AHL _{sitting}		0.35	0.03	0.38	0.03	0.40	0.03	14.05	0.001	0.000	0.004	0.012
AHL _{standing}		0.33	0.03	0.36	0.03	0.38	0.03	13.76	0.001	0.000	0.004	0.008
AHF (mm/kN)		13.03	5.90	13.21	1.51	12.13	7.34	0.36	0.837			

Table Ib: Gait Pattern		Planus		Rectus		Cavus		GEE Results		Post-hoc Analysis (p-values)		
		Mean	SD	Mean	SD	Mean	SD	χ^2	p-value	P v C	P v R	R v C
Cadence (steps/min)		115.54	10.68	117.70	8.44	112.40	9.70	2.61	0.272			
Stride Length (m)		1.36	0.12	1.31	0.11	1.35	0.18	2.50	0.290			
Step Length (m)		0.65	0.06	0.65	0.06	0.68	0.09	2.60	0.273			
Velocity (m/s)		1.31	0.18	1.28	0.15	1.26	0.21	0.53	0.770			
Gait Cycle Time (s)		1.05	0.09	1.03	0.07	1.08	0.09	2.87	0.238			
Stance Time (s)		0.62	0.06	0.61	0.05	0.65	0.06	2.60	0.272			
Normalized Stance Time		0.59	0.02	0.60	0.01	0.60	0.01	6.23	0.044	0.009	0.054	0.382
Swing Time (s)		0.42	0.04	0.41	0.03	0.43	0.04	3.51	0.170			
Double Support Time (s)		0.10	0.02	0.10	0.02	0.11	0.02	3.96	0.138			
Normalized Double Support Time		0.09	0.01	0.10	0.01	0.10	0.10	6.37	0.041	0.004	0.127	0.157

Conditions of analysis:

N=61 test subjects (Nplanus = 22, Nrectus = 27, Ncavus = 12). C = cavus; R = rectus; P = planus.

Foot types classified using goniometric measures of Resting Calcaneal Stance Position (RCSP) and Forefoot to Rearfoot Angle (FF-RF)

All data is bilateral (right and left feet)

Each parameter was calculated for each of 5 trials and averaged to represent an unbiased estimate of 122 feet.

GEE implementation: Linear (Normal, Identity) Link Function; maximum likelihood estimation method; Correlation type=Exchangeable

GEE p values were determined by the general score χ^2 statistics. Post hocs are interpreted with a Bonferroni adjustment $P<0.01667$

Note: only those normalized values that exhibit a significant difference are included and shown in italics

Result Summary for Peak Pressure (PP) and Maximum Force (MF) Parameters Across Foot Type for Asymptomatic Test Subjects

Table II

Table IIa: PP (N/cm ²)		Planus		Rectus		Cavus		GEE Results		Post-hoc Analysis (p-values)		
		Mean	SD	Mean	SD	Mean	SD	χ^2	p-value	P v C	P v R	R v C
Hallux		45.32	16.15	36.69	17.31	29.05	13.68	9.27	0.010	0.000	0.042	0.092
Normalized Hallux		0.74	0.21	0.64	0.28	0.53	0.23	7.73	0.021	0.002	0.105	0.155
Toe 2		20.11	9.56	14.66	7.07	12.05	7.14	8.28	0.016	0.001	0.014	0.209
Toes 3-5		12.39	5.74	11.16	5.38	9.64	6.76	1.952	0.377			
MH1		29.39	16.70	35.80	22.25	33.38	16.18	1.48	0.480			
MH2		50.42	19.72	37.84	12.28	37.82	12.42	7.42	0.024	0.013	0.004	0.996
Normalized MH2		0.81	0.20	0.67	0.21	0.70	0.19	7.35	0.025	0.071	0.004	0.606
MH1/MH2		0.66	0.50	1.07	0.78	0.98	0.63	5.59	0.061			
MH3		39.37	14.61	34.53	8.71	35.58	7.03	2.04	0.360			
MH4		27.03	7.97	26.30	8.55	26.93	9.40	0.13	0.938			
MH5		22.49	14.66	24.22	15.11	26.86	14.78	0.82	0.664			
Medial Arch		9.71	5.00	9.59	4.09	6.57	4.93	4.00	0.135			
Lateral Arch		10.90	4.01	11.12	4.38	8.89	5.29	1.56	0.460			
Medial Heel		37.20	11.30	37.18	13.51	39.12	12.39	0.22	0.894			
Lateral Heel		33.70	7.53	34.20	10.23	39.26	12.37	2.16	0.340			
Total PP		62.39	17.31	58.92	16.14	55.14	11.75	2.32	0.314			
CPFI (%)		18.57	4.97	21.65	5.47	24.10	8.12	8.54	0.014	0.010	0.010	0.263

Table IIb: MF (N)		Planus		Rectus		Cavus		GEE Results		Post-hoc Analysis (p-values)		
		Mean	SD	Mean	SD	Mean	SD	χ^2	p-value	P v C	P v R	R v C
Hallux		133.92	46.79	110.1	40.91	83.93	34.69	10.39	0.006	0.000	0.039	0.017
Normalized Hallux		0.186	0.062	0.164	0.067	0.124	0.055	7.80	0.020	0.001	0.206	0.028
Toe 2		25.73	11.66	18.37	10.03	15.67	11.12	8.20	0.017	0.003	0.010	0.379
Normalized Toe 2		0.037	0.017	0.027	0.015	0.023	0.015	7.01	0.030	0.005	0.030	0.346
Toes 3-5		25.56	16.49	20.15	13.03	17.33	13.24	3.15	0.207			
MH1		129.78	49.33	151.72	60.47	151.17	44.44	2.830	0.243			
Normalized MH1		0.175	0.052	0.218	0.074	0.222	0.068	7.964	0.019	0.016	0.008	0.855
MH2		172.12	46.56	152.33	39.37	153.53	45.38	2.76	0.252			
MH1/MH2		0.78	0.32	1.06	0.50	1.06	0.43	7.41	0.025	0.025	0.011	0.962

Table IIb: MF (N)

MH3	168.35	53.23	151.43	37.33	158.79	48.60	1.71	0.425		
MH4	102.51	32.32	98.14	31.93	112.18	52.86	0.86	0.650		
MH5	42.84	17.98	49.05	26.59	67.10	35.35	4.84	0.089		
Normalized MH5	<i>0.064</i>	<i>0.029</i>	<i>0.069</i>	<i>0.029</i>	<i>0.092</i>	<i>0.035</i>	<i>6.22</i>	<i>0.045</i>	<i>0.004</i>	<i>0.255</i>
Medial Arch	24.99	31.54	14.41	11.42	6.89	8.03	6.90	0.032	0.008	0.125
Normalized Medial Arch	<i>0.030</i>	<i>0.033</i>	<i>0.021</i>	<i>0.015</i>	<i>0.009</i>	<i>0.009</i>	<i>8.66</i>	<i>0.013</i>	<i>0.003</i>	<i>0.216</i>
Lateral Arch	98.38	76.17	81.81	56.56	71.56	70.13	0.96	0.618		
Medial Heel	266.93	43.50	253.13	50.79	247.48	65.19	1.36	0.506		
Lateral Heel	220.86	41.68	215.83	50.46	213.93	47.27	0.19	0.912		
Total MF	733.16	158.10	690.98	125.24	703.38	162.64	1.05	0.592		

Conditions of analysis:

N=61 test subjects (Nplanus = 22, Nrectus = 27, Ncavus = 12). C = cavus; R = rectus; P = planus.

Foot types classified using goniometric measures of Resting Calcaneal Stance Position (RCSP) and Forefoot to Rearfoot Angle (FF-RF)

All data is bilateral (right and left feet)

Each parameter was calculated for each of 5 trials and averaged to represent an unbiased estimate of 122 feet

GEE implementation: Linear (Normal, Identity) Link Function; maximum likelihood estimation method; Correlation type=Exchangeable

GEE p values were determined by the general score χ^2 statistics. Post hoc are interpreted with a Bonferroni adjustment $P < 0.01667$

Note: only those normalized values that exhibit a significant difference are included and shown in italics

Table III

Result Summary for PTI, FTL, and Area Across Foot Type for Asymptomatic Test Subjects

Table IIIa: PTI (Ns/cm ²)	Planus		Rectus		Cavus		GEE Results		Post-hoc Analysis (p-values)		
	Mean	SD	Mean	SD	Mean	SD	χ^2	p-value	P v C	P v R	R v C
Hallux	8.4	3.4	7.4	3.8	5.5	2.6	7.68	0.023	0.001	0.268	0.036
Toe 2	3.2	1.4	2.7	1.4	2.4	1.8	3.11	0.211			
Toes 3-5	2.2	1.2	1.9	1.1	2.0	1.6	0.96	0.617			
MH1	7.0	3.2	8.4	4.7	7.9	3.2	2.01	0.367			
MH2	11.3	4.5	9.4	3.7	9.5	3.6	3.05	0.218			
MH3	9.7	4.0	9.0	2.7	9.9	2.1	1.47	0.480			
MH4	6.9	2.0	7.4	2.7	8.0	2.3	2.47	0.291			
MH5	5.1	2.5	6.4	3.9	7.2	2.9	5.31	0.070			
Normalized MH5	0.03	0.02	0.04	0.02	0.06	0.02	9.49	0.009	0.000	0.084	0.011
Medial Arch	2.1	1.1	2.0	1.0	1.3	1.0	5.32	0.070			
Normalized Medial Arch	0.013	0.013	0.009	0.007	0.004	0.004	9.00	0.011	0.001	0.192	0.001
Lateral Arch	3.0	1.3	3.0	1.4	2.7	1.8	0.19	0.909			
Medial Heel	7.9	2.2	7.5	2.6	8.1	2.4	0.63	0.731			
Lateral Heel	7.3	1.8	6.9	1.6	7.7	2.1	2.07	0.355			

Table IIIb: FTL (Ns)

Hallux	22.9	9.7	20.5	9.0	15.5	7.2	6.42	0.040	0.004	0.317	0.033
Normalized Hallux	0.41	0.14	0.39	0.19	0.28	0.12	8.59	0.014	0.000	0.480	0.012
Toe 2	4.0	2.2	3.2	2.3	2.9	2.4	3.03	0.220			
Toes 3-5	4.0	3.0	3.0	2.3	3.1	2.6	2.13	0.344			
MH1	31.9	14.8	36.8	18.0	35.4	11.1	1.30	0.522			
MH2	46.2	17.3	40.8	15.9	40.2	12.5	1.70	0.427			
MH3	46.8	19.0	43.4	14.0	47.4	13.8	1.03	0.598			
MH4	29.0	10.8	29.9	12.7	35.4	15.8	1.61	0.446			
MH5	11.0	5.1	13.8	8.7	19.2	9.5	7.33	0.026	0.003	0.136	0.072
Normalized MH5	0.25	0.12	0.32	0.15	0.38	0.17	6.44	0.040	0.013	0.065	0.244
Medial Arch	4.76	5.82	2.76	2.36	1.28	1.55	7.09	0.029	0.006	0.12	0.008
Lateral Arch	24.99	21.35	20.67	17.59	19.03	20.78	0.68	0.711			

Table IIIb: FTI (Ns)

Medial Heel	57.14	14.71	53.34	15.25	51.50	9.56	1.65	0.438
Lateral Heel	47.78	13.74	45.08	14.29	44.20	8.61	0.84	0.659

Table IIIc: Area (cm²)

Hallux	10.080	1.821	9.672	1.602	9.654	1.537	0.92	0.630		
Toe 2	3.539	0.813	2.994	0.983	2.796	1.213	6.73	0.035	0.033	0.578
Toes 3-5	5.618	2.349	4.807	2.297	4.567	2.553	2.24	0.327		
MH1	12.355	2.824	11.478	1.583	12.188	2.065	2.457	0.293		
MH2	10.218	2.327	9.244	1.336	9.158	1.616	3.35	0.188		
MH3	11.307	2.307	10.341	1.506	10.650	2.123	2.84	0.242		
MH4	9.370	1.826	8.685	1.131	9.488	1.766	3.78	0.151		
Normalized MH4	<i>0.075</i>	<i>0.008</i>	<i>0.077</i>	<i>0.008</i>	<i>0.084</i>	<i>0.007</i>	<i>8.61</i>	0.013	0.000	0.473
MH5	5.284	1.275	5.146	0.836	6.258	1.182	6.41	0.040	0.020	0.649
Normalized MH5	<i>0.042</i>	<i>0.007</i>	<i>0.046</i>	<i>0.006</i>	<i>0.055</i>	<i>0.006</i>	<i>13.68</i>	0.001	0.000	0.000
Medial Arch	4.859	5.511	2.669	1.539	1.367	1.161	7.94	0.019	0.003	0.001
Normalized Medial Arch	<i>0.034</i>	<i>0.032</i>	<i>0.023</i>	<i>0.012</i>	<i>0.011</i>	<i>0.008</i>	<i>9.92</i>	0.007	0.001	0.113
Lateral Arch	19.680	8.656	16.783	8.260	14.170	10.117	2.49	0.288		
Medial Heel	16.768	2.714	16.015	1.936	16.278	2.520	1.29	0.526		
Lateral Heel	16.839	2.661	15.967	1.866	16.196	2.557	1.74	0.418		

Conditions of analysis:

N=61 test subjects (N_{planus} = 22, N_{rectus} = 27, N_{cavus} = 12); C =cavus; R =rectus; P =planus.

Foot types classified using goniometric measures of Resting Calcaneal Stance Position (RCSP) and Forefoot to Rearfoot Angle (FF-RF)

All data is bilateral (right and left feet)

Each parameter was calculated for each of 5 trials and averaged to represent an unbiased estimate of 122 feet

GEE p values were determined by the general score χ^2 statistics.

GEE implementation: Linear (Normal, Identity) Link Function; maximum likelihood estimation method; Correlation type=Exchangeable

Post hoc are interpreted with a Bonferroni adjustment P<0.01667

Note: only those normalized values that exhibit a significant difference are included and shown in italics