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Foot Type Biomechanics Part 2: Are structure and anthropometrics related to function?

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Abstract

Background—Many foot pathologies are associated with specific foot types. If foot structure and function are related, measurement of either could assist with differential diagnosis of pedal pathologies.

Hypothesis—Biomechanical measures of foot structure and function are related in asymptomatic healthy individuals.

Methods—Sixty-one healthy subjects' left feet were stratified into cavus ($n = 12$), rectus ($n = 27$) and planus ($n = 22$) foot types. Foot structure was assessed by malleolar valgus index, arch height index, and arch height flexibility. Anthropometrics (height and weight), age, and walking speed were measured. Foot function was assessed by center of pressure excursion index, peak plantar pressure, maximum force, and gait pattern parameters. Foot structure and anthropometric variables were entered into stepwise linear regression models to identify predictors of function.

Results—Measures of foot structure and anthropometrics explained 10–37% of the model variance (adjusted R^2) for gait pattern parameters. When walking speed was included, the adjusted R^2 increased to 45–77% but foot structure was no longer a factor. Foot structure and anthropometrics predicted 7–47% of the model variance for plantar pressure and 16–64% for maximum force parameters. All multivariate models were significant ($p < 0.05$), supporting acceptance of the hypothesis.

Discussion and conclusion—Foot structure and function are related in asymptomatic healthy individuals. The structural parameters employed are basic measurements that do not require

ionizing radiation and could be used in a clinical setting. Further research is needed to identify additional predictive parameters (plantar soft tissue characteristics, skeletal alignment, and neuromuscular control) and to include individuals with pathology.

Keywords

Foot and ankle; Gait; Foot type; Plantar pressures; Structure and function

1. Introduction

Many foot pathologies are of a biomechanical nature and associated with foot type [1–4]. Foot type is a morphological description that combines structural differences in alignment and arch height to categorize feet as either planus (flat), rectus (well aligned), or cavus (high arched). Song et al. [5] utilized malleolar valgus index (MVI), a measure of hindfoot alignment, and center of pressure excursion index (CPEI), a measure of dynamic foot pronation, to successfully discriminate planus from rectus feet. This study did not include cavus feet nor predict foot function from measures of foot structure. Cavanagh et al. [6] examined the relationship between radiographic measures of foot structure and pressure beneath both the 1st metatarsal head (MH1) and heel and demonstrated the feasibility of the concept that structure is related to function. They did not identify the foot types included in their data set or assess the function of the foot in other anatomical regions. As described in ‘Foot Type Biomechanics Part 1: Structure and Function of the Asymptomatic Foot’, several variables of foot structure and function have demonstrated significant differences across the planus, rectus, and cavus foot types [7]. An in-depth investigation of the relationship between foot structure and function is still needed.

Measures of foot structure are clinically practical and less costly than those of foot function. The ability to relate foot structure to foot function would assist the clinician who can practically measure foot structure but not function with differential diagnosis of foot pathologies, treatment planning, and determination of treatment efficacy.

The aim of this study is to determine if measures of foot structure and individual anthropometrics can predict foot function. The hypothesis is: biomechanical measures of foot structure (hindfoot alignment, arch height, and arch flexibility), anthropometrics (height and weight), age, and walking speed are related to function (plantar loading and gait pattern) in asymptomatic healthy individuals.

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 were recruited for enrollment into this investigation. Participants were between 18 and 77 years old with no current symptoms of pain, had no foot and ankle pathology, and were able to walk independently. Individuals with neuromusculoskeletal disease, prior foot or lower extremity surgery in the previous year, or uncontrolled cardiovascular disease were excluded. Based on clinical examination, the participants included the following foot types: planus ($n = 22$), rectus ($n = 27$) and cavus ($n = 12$). Foot Type Biomechanics Part 1 [7] contains the foot type classification criteria, a description of each structural and functional parameter, and an illustration of the corresponding measurement techniques.

2.2. Measures of Foot Structure

In addition to the clinical goniometric-based assessments, several measures of foot structure were performed on each participant.

1. Malleolar Valgus Index, MVI (%), is a measure of standing hind foot alignment [5]. MVI is the deviation of the transmalleolar midpoint relative to the longitudinal foot bisection, normalized to ankle width [5].
2. Arch Height Index, AHI (%), is the dorsal arch height at one half the foot length normalized by the truncated foot length [8].
3. Arch Height Flexibility, AHF (mm/kN), is the change in arch height between sitting and standing conditions normalized to the change in load (estimated as 40% of body weight) [8].

2.3. Measures of foot function

Dynamic foot function was assessed with plantar loading and gait pattern parameters for each subject walking at their self-selected speed. Plantar loading parameters included: (1) CPEI (%) [5], (2) peak plantar pressure, PP (N/cm²), (3) maximum force, MF(N), and (4) area (cm²). PP, MF and area were calculated for each of the 12 masked regions of the maximum pressure plot as measured by the emed-x (Novel, Munich, Germany). Gait pattern parameters, quantified by GaitMatII (EQ Inc., Chalfont, PA, USA), included: stride length, step length, double support time, walking speed, cadence, step time, gait cycle time, swing time, and stance time.

2.4. Statistical analysis

The data from individuals of all three foot types were pooled in this analysis to reflect the range and variability seen in the general population. A stepwise regression model was employed to determine which structural and anthropometric parameters were related to each measure of function. This type of analysis does not compensate for potential dependence between cases. The left foot was arbitrarily chosen so that the p and R^2 values would not be artificially improved.

Foot structure variables (MVI, AHI, AHF, and clinical goniometric measures), anthropometrics (height and weight), age, and walking speed were entered into a stepwise linear regression, using SPSS software (IBM, Chicago, IL, USA) to identify predictors of each measure of dynamic foot function (plantar loading and gait pattern parameters). At each step, independent variables were entered into the regression equation if $p < 0.05$ and removed if $p > 0.10$. The method terminated when no more variables were eligible for inclusion or removal. R^2 values were calculated to assess the proportion of variance in the dependent variable explained by the independent variables. The adjusted R^2 values were corrected for multiple independent variables. This analysis was run twice: with and without walking speed as a potential dependent variable.

3. Results

3.1. Gait pattern parameter models

Models were constructed to estimate the gait parameters for each of the following dependent variables: stride length, step length, walking speed, swing time, stance time, gait cycle time, cadence, step time, and double support time (Table 1). When walking speed was not included, R values ranged from 0.34 to 0.62 with adjusted R^2 values explaining between 10% and 37% of the corresponding model variance. When walking speed was included, R values ranged from 0.68 to 0.88 with adjusted R^2 values explaining between 45% and 77%

of the corresponding model variance. Upon analysis of the gait pattern parameters, step length demonstrated the highest correlation with structural and anthropometric variables, defined by the equation

$$\text{Step length} = (0.003 \times \text{Ht}) - (0.474 \times \text{AHI}_{\text{sitting}}) + 0.348 \quad (1)$$

where Ht is the height in cm. When walking speed was considered in the model, the correlation increased and Eq. (1) became

$$\text{Step length} = (0.003 \times \text{Ht}) - (0.257 \times \text{WS}) - 0.112 \quad (2)$$

where walking speed (WS) displaced $\text{AHI}_{\text{sitting}}$. WS replaced the foot structure variable in all gait parameter models (Table 1). The model for WS included $\text{AHI}_{\text{sitting}}$ where individuals with lower arches walked faster than those with higher arches.

3.2. Plantar pressure models

Plantar pressure regression models were created for CPEI and PP in each of the masked regions. R values ranged from 0.29 to 0.72 with adjusted R^2 values explaining between 7% and 47% of the corresponding model variance (Table 2). Of the plantar pressure parameters, peak pressure in the medial arch (PP-medial arch), a variable that distinguished different foot types, [7] demonstrated the highest correlation with structural and anthropometric variables

$$\text{PP-medial arch} = (0.107 \times \text{TA}) + (64.725 \times \text{AHI}_{\text{sitting}}) - (0.102 \times \text{Age}) + (0.459 \times \text{FF} - \text{RF}) - 25.491 \quad (3)$$

where TA is the total contact area. In addition to TA, PP-medial arch was related to age, $\text{AHI}_{\text{sitting}}$, and the FF-RF relationship. Planus feet had a lower $\text{AHI}_{\text{sitting}}$ than cavus and rectus feet, which, as expected, would increase plantar pressure in the medial arch.

3.3. Maximum force models

Predictive MF models were formed for each of the masked regions. R values ranged from 0.42 to 0.82. Adjusted R^2 values explained between 16% and 64% of the corresponding model variance (Table 3). Total MF demonstrated the highest correlation with its predictive variables.

$$\text{Total MF} = (3.086 \times \text{TA}) + (6.224 \times \text{Ht}) + (1530.055 \times \text{AHI}_{\text{sitting}}) + (13.043 \times \text{FF} - \text{RF}) - 319.403 \quad (4)$$

Total MF was also related to height and foot structure ($\text{AHI}_{\text{sitting}}$, FF-RF).

4. Discussion

This study was conducted to investigate the relation between foot structure, anthropometrics, and function. Measurements of foot function require specialized equipment and are not usually practical during clinical examination, whereas measurements of foot structure are easily accomplished in a clinical setting. The structural measures of AHI and MVI have demonstrated ICC values between 0.81 and 1.0 for intra- and inter-rater reliability [5,9,10]. The functional measures, CPEI, PP, and MF, have demonstrated ICC values between 0.61 and 0.80 for test-retest and between day reliability [5,11]. The model parameter ICC values were considered sufficient for confident model predictions. In the current study, 48 multivariate models were formed to predict gait pattern parameters, regional peak plantar

pressures, and distributed maximum forces of asymptomatic individuals. All multivariate models were significant ($p < 0.05$) so the hypothesis (biomechanical measures of foot structure, anthropometrics, and walking speed are related to function in asymptomatic healthy individuals) was accepted.

4.1. Gait pattern parameter prediction

When modeling the gait pattern parameters, stride length and step length yielded the highest adjusted R^2 values, which explained 32% and 37% of the model variance, respectively. Stride and step length were positively related to height, which was consistent with the observation that taller individuals have longer limb lengths. AHI_{sitting} , a parameter more indicative of foot type, was negatively related to stride length, implying that individuals with a lower arch height have longer stride lengths. When walking speed was entered into these models, AHI_{sitting} was no longer significant. The adjusted R^2 values raised to 77% of the model variance for both stride and step length. The adjusted R^2 values for each gait pattern parameter increased when walking speed was entered into the model (Table 1), thus walking speed is a more important factor when modeling gait pattern than foot structure.

4.2. Plantar pressure parameter prediction

PP-medial arch, PP-lateral arch and CPEI yielded the highest adjusted R^2 values for all plantar pressure models, which explained 47%, 47%, and 35% of the model variance respectively (Table 2). CPEI was positively related to RCSP, implying that a varus hindfoot (excessive supination) has higher CPEI values (more concave COP curve). The arch is an important load-bearing region of the foot that is very sensitive to foot type. Feet with low arches are likely to have higher medial arch loading, while feet with high arches are likely to have higher lateral arch loading [12,13]. In cases of extreme arch height there may be no midfoot loading, leaving the heel and metatarsal heads to bear the load of the foot [14]. PP-medial arch and PP-lateral arch models also included a positive relationship to AHI_{sitting} and a negative relationship to age. Lower AHI_{sitting} would be associated with a planus foot type and a lower lateral arch pressure [12]. Including age in the model indicates that, as individuals age, the arch lowers. This is in contrast to a study of similarly aged individuals that found no significant relationship between arch height and age [8]. PP-medial arch was also positively associated with FF–RF relationship. Higher varus FF–RF relationships would promote excessive pronation and increase peak pressures in the medial arch.

4.3. Maximum force parameter prediction

Total force, MF-lateral arch, and MF-MH3 yielded the highest adjusted R^2 values, which explained 64%, 58%, and 50% of the model variance, respectively. Total force was positively related to contact area, height, and AHI_{sitting} which was consistent with the observation that heavier individuals have larger feet, are taller in stature, and have a higher arch height. This means that cavus feet are associated with greater total forces in gait. Adding height to the predictive model follows from considering height–weight charts in children and adults. MF-lateral arch and MF-MH3 were both positively related to contact area. MF-MH3 was also positively related to height and negatively related to walking speed. As expected, MF-medial arch was positively predicted by total contact area because both were associated with foot type. As TA increases (e.g. due to planus feet) loads increase in the medial arch. An inverse relationship with height means that taller individuals have lower forces in the medial arch or exhibit less prevalence of planus feet. On average, the taller individual weighs more and imparts a greater plantar force.

4.4. Foot structure and function models

The fundamental concept that foot structure and function may be related has been suggested by a number of investigators [1,15–26]. Song et al. examined rectus and planus feet using MVI and CPEI [5] and demonstrated that the planus and rectus foot types resulted in biomechanically distinct foot functions. The following limitations were noted: only one structural variable (MVI) was considered, the sample size was small, and cavus feet were not included in the analysis.

Motivated by the Song et al. study [5], the current investigation included additional structural variables, increased the sample size, and included cavus feet.

Cavanagh et al. [6] predicted peak pressure values in the heel and MH1 from radiographic measures. By combining measures of foot structure and function these investigators predicted approximately 50% of the variance in peak pressure. In the current investigation 18%, 26%, 27%, 47% and 47% of the variance in PP could be accounted for beneath the hallux, MH1, lateral heel, lateral arch and medial arch, respectively. The approach used by Cavanagh et al. [6] and Morag and Cavanagh [15] required anterior–posterior and lateral X-ray views of the foot and other measures requiring specialized instrumentation. The structural (MVI and AHI), anthropometric (RCSP, FF–RF, weight, and height), and age parameters in this investigation are all non-ionizing measurements that can be done in a clinician's office. The models predicted PP and MF in 12 plantar regions as well as CPEI and 10 gait pattern parameters. The current study adds to the body of literature by describing foot function in subjects with a distribution of foot types.

4.5. Application to pathology

Models have been developed to predict gait speed in elders [27] and hemiparetic stroke patients [28] as well as falls in a cohort of elders with increased gait variability [29]. Menz et al. [30] hypothesized that individuals with midfoot OA have flatter feet and generate greater forces through the plantar midfoot while walking. In the current study, MF-medial arch was highest in those individuals with planus feet [7]. Furthermore, MF-medial arch was positively related to TA. Both findings in an asymptomatic population are consistent with that of Menz et al., suggesting that foot structure maybe a more important determinant of foot function than the presence of pathology (midfoot OA).

4.6. Study limitations

Several potential limitations to this investigation exist. Group sample sizes were unbalanced, with relatively fewer individuals with cavus ($n = 12$) compared to rectus ($n = 27$) and planus ($n = 22$) feet. Other structurally predictive factors that could describe foot function were not included, which could have explained additional variance in the models. Foot function may in part be affected by structural alignment, as measured in this study, but also by the specific geometry of the foot. Anatomical details, such as calcaneal and hallucial fat pad thickness, as well as the compliant nature of the flexor plate region beneath each metatarsalphalangeal joint, are likely to provide cushioning and could affect foot function during gait. Finally, given that gait is a dynamic activity, it may not be reasonable to expect that all of the variance be explained by static measures. As an example, the neuromuscular control of these structures will likely also be an important determinant of foot function.

4.7. Clinical importance

With 28 bones, 33 joints, and 112 ligaments the foot is one of the more mechanically complex structures in the body. Pathology is often associated with malalignment, deformity, or damage to one or more of the foot structures. If foot structure is related to foot function,

then measurement of either could assist with differential diagnosis of pedal pathologies, treatment planning, and determination of treatment efficacy. The measures of foot structure are less costly than foot function and more feasible to be performed in the clinical setting.

5. Conclusion

Several measures of foot structure (AHI_{sitting} , AHI_{standing} , RCSP, FF-RF, and TA), anthropometrics (height and weight), age, and walking speed were related to biomechanical measures of foot function (PP, MF, CPEI, and gait pattern parameters) in asymptomatic healthy individuals with planus, rectus, and cavus foot types. Measures of foot structure and anthropometrics explained 10–37% of the model variance (adjusted R^2) for gait pattern parameters. When walking speed was included, the adjusted R^2 increased to 45–77% but foot structure was no longer a factor in those models. Foot structure and anthropometrics predicted 7–47% of the model variance for plantar pressure and 16–64% for maximum force parameters. Based upon these results, foot structure and anthropometrics were related to foot function. The structural parameters used were basic measurements that do not require ionizing radiation and can be employed in a clinical office setting.

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References

1. Ledoux WR, Shofer JB, Ahroni JH, Smith DG, Sangeorzan BJ, Boyko EJ. Biomechanical differences among pes cavus, neutrally aligned, and pes planus feet in subjects with diabetes. *Foot and Ankle International*. 2003; 24:845–50. [PubMed: 14655889]
2. Naudi S, Dauplat G, Staquet V, Parent S, Mehdi N, Maynou C. Anterior tarsectomy long-term results in adult pes cavus. *Orthopaedics and Traumatology-Surgery and Research*. 2009; 95:293–300.
3. Sugathan HK, Sherlock DA. A modified Jones procedure for managing clawing of lesser toes in pes cavus: long-term follow-up in 8 patients. *Journal of Foot and Ankle Surgery*. 2009; 48:637–41. [PubMed: 19857818]
4. Levy JC, Mizel MS, Wilson LS Jr, Fox W, McHale K, Taylor DC, et al. Incidence of foot and ankle injuries in West Point cadets with pes planus compared to the general cadet population. *Foot and Ankle International*. 2006; 27:1060–4. [PubMed: 17207433]
5. Song J, Hillstrom HJ, Secord D, Levitt J. Foot type biomechanics. Comparison of planus and rectus foot types. *Journal of the American Podiatric Medical Association*. 1996; 86:16–23. [PubMed: 8808320]
6. Cavanagh PR, Morag E, Boulton AJ, Young MJ, Deffner KT, Pammer SE. The relationship of static foot structure to dynamic foot function. *Journal of Biomechanics*. 1997; 30:243–50. [PubMed: 9119823]
7. Hillstrom HJ, Song J, Kraszewski AP, Hafer JF, Mootanah R, Dufour AB, et al. Foot type biomechanics part 1: Structure and function of the asymptomatic foot. *Gait Posture*. 2013; 37:445–51. [PubMed: 23107625]
8. Zifchock RA, Davis I, Hillstrom HJ, Song J. The effect of gender, age, and lateral dominance on arch height and arch stiffness. *Foot and Ankle International*. 2006; 27:367–72. [PubMed: 16701058]
9. Richards CJ, Card K, Song J, Hillstrom HJ. A novel arch height index measurement system (AHIMS): intra- and inter-rater reliability. *International Society of Biomechanics*. 2003
10. Butler C. Walking 101. Putting one foot in front of the other can put you ahead of the game. *Diabetes Forecast*. 2008; 61:31–4. [PubMed: 18478641]

11. Gurney JK, Kersting UG, Rosenbaum D. Between-day reliability of repeated plantar pressure distribution measurements in a normal population. *Gait and Posture*. 2008; 27:706–9. [PubMed: 17693087]
12. Goffar SL, Naylor J, Reber RJ, Rodriguez BM, Christiansen BC, Walker MJ, et al. Dynamic plantar pressure changes during loaded gait. *US Army Medical Department Journal*. 2010 Jul-Sep;:77.
13. Crosbie J, Burns J, Ouvrier RA. Pressure characteristics in painful pes cavus feet resulting from Charcot-Marie-Tooth disease. *Gait and Posture*. 2008; 28:545–51. [PubMed: 18456499]
14. Xiong S, Goonetilleke RS, Witana CP, Weerasinghe TW, Au EY. Foot arch characterization: a review, a new metric, and a comparison. *Journal of the American Podiatric Medical Association*. 2010; 100:14–24. [PubMed: 20093541]
15. Morag E, Cavanagh PR. Structural and functional predictors of regional peak pressures under the foot during walking. *Journal of Biomechanics*. 1999; 32:359–70. [PubMed: 10213026]
16. McPoil TG, Vicenzino B, Cornwall MW, Collins N. Can foot anthropometric measurements predict dynamic plantar surface contact area? *Journal of Foot and Ankle Research*. 2009; 2:28. [PubMed: 19863799]
17. Teyhen DS, Stoltzenberg BE, Collinsworth KM, Giesel CL, Williams DG, Kardouni CH, et al. Dynamic plantar pressure parameters associated with static arch height index during gait. *Clinical Biomechanics (Bristol Avon)*. 2009; 24:391–6.
18. Mueller MJ, Hastings M, Commeyan PK, Smith KE, Pilgram TK, Robertson D, et al. Forefoot structural predictors of plantar pressures during walking in people with diabetes and peripheral neuropathy. *Journal of Biomechanics*. 2003; 36:1009–17. [PubMed: 12757810]
19. Ledoux WR, Hillstrom HJ. Acceleration of the calcaneus at heel strike in neutrally aligned and pes planus feet. *Clinical Biomechanics (Bristol Avon)*. 2001; 16:608–13.
20. Aquino A, Payne C. Function of the windlass mechanism in excessively pronated feet. *Journal of the American Podiatric Medical Association*. 2001; 91:245–50. [PubMed: 11359889]
21. Ledoux WR, Shofer JB, Smith DG, Sullivan K, Hayes SG, Assal M, et al. Relationship between foot type, foot deformity, and ulcer occurrence in the high-risk diabetic foot. *Journal of Rehabilitation Research and Development*. 2005; 42:665–72. [PubMed: 16586192]
22. Ledoux WR, Hillstrom HJ. The distributed plantar vertical force of neutrally aligned and pes planus feet. *Gait and Posture*. 2002; 15:1–9. [PubMed: 11809575]
23. Nigg BM, Fisher V, Allinger TL, Ronsky JR, Engsberg JR. Range of motion of the foot as a function of age. *Foot and Ankle*. 1992; 13:336–43. [PubMed: 1398363]
24. Nachbauer W, Nigg BM. Effects of arch height of the foot on ground reaction forces in running. *Medicine and Science in Sports and Exercise*. 1992; 24:1264–9. [PubMed: 1359377]
25. McPoil TG, Cornwall MW. Relationship between three static angles of the rearfoot and the pattern of rearfoot motion during walking. *Journal of Orthopaedic and Sports Physical Therapy*. 1996; 23:370–5. [PubMed: 8727017]
26. Faria A, Gabriel R, Abrantes J, Bras R, Moreira H. The relationship of body mass index, age and triceps-surae musculotendinous stiffness with the foot arch structure of postmenopausal women. *Clinical Biomechanics (Bristol Avon)*. 2010; 25:588–93.
27. Callisaya ML, Blizzard L, Schmidt MD, McGinley JL, Lord SR, Srikanth VK. A population-based study of sensorimotor factors affecting gait in older people. *Age and Ageing*. 2009; 38:290–5. [PubMed: 19264860]
28. Wong AM, Pei YC, Hong WH, Chung CY, Lau YC, Chen CP. Foot contact pattern analysis in hemiplegic stroke patients: an implication for neurologic status determination. *Archives of Physical Medicine and Rehabilitation*. 2004; 85:1625–30. [PubMed: 15468022]
29. Brach JS, Berthold R, Craik R, VanSwearingen JM, Newman AB. Gait variability in community-dwelling older adults. *Journal of the American Geriatrics Society*. 2001; 49:1646–50. [PubMed: 11843998]
30. Menz HB, Munteanu SE, Zammit GV, Landorf KB. Foot structure and function in older people with radiographic osteoarthritis of the medial midfoot. *Osteoarthritis and Cartilage*. 2010; 18:317–22. [PubMed: 19948268]

Table 1

Gait pattern parameter model summary.

Dependent variable	Speed included	Multivariate stepwise regression model	R	R ²	Adj R ²	Sig. F change
Cadence (steps/min)	No	$(-0.028 \times \text{Wt}) + 134.744$	0.42	0.18	0.16	0.001
Cadence (steps/min)	Yes	$(42.500 \times \text{WS}) - (0.437 \times \text{Ht}) + 135.112$	0.84	0.71	0.70	0.000
Double support time (s)	No	$(6.132\text{E}-5 \times \text{Wt}) + 0.058$	0.49	0.24	0.23	0.000
Double support time (s)	Yes	$(-0.066 \times \text{WS}) + (0.149 \times \text{Wt}) + 0.149$	0.79	0.63	0.61	0.000
Gait cycle time (s)	No	$(0.03 \times \text{Ht}) + 0.514$	0.41	0.16	0.15	0.002
Gait cycle time (s)	Yes	$(-0.374 \times \text{WS}) + (0.004 \times \text{Ht}) + 0.867$	0.83	0.70	0.68	0.000
Stance time (s)	No	$(1.8\text{E}-4 \times \text{Wt}) + 0.501$	0.45	0.20	0.19	0.001
Stance time (s)	Yes	$(-0.257 \times \text{WS}) + (0.003 \times \text{Ht}) + 0.512$	0.85	0.72	0.71	0.000
Step length (m)	No	$(0.003 \times \text{Ht}) - (0.474 \times \text{AHL}_{\text{sitting}}) + 0.348$	0.62	0.39	0.37	0.012
Step length (m)	Yes	$(0.257 \times \text{WS}) + (0.003 \times \text{Ht}) - 0.112$	0.88	0.78	0.77	0.000
Step time (s)	No	$(0.002 \times \text{Ht}) + 0.260$	0.41	0.17	0.15	0.002
Step time (s)	Yes	$(-0.175 \times \text{WS}) + (0.002 \times \text{Ht}) + 0.426$	0.81	0.65	0.64	0.000
Stride Length (m)	No	$(0.006 \times \text{Ht}) - (0.945 \times \text{AHL}_{\text{sitting}}) + 0.729$	0.59	0.35	0.32	0.018
Stride length (m)	Yes	$(0.55 \times \text{WS}) + (0.005 \times \text{Ht}) - 0.222$	0.88	0.78	0.77	0.000
Swing time (s)	No	$(0.001 \times \text{Ht}) + 0.244$	0.35	0.12	0.11	0.008
Swing time (s)	Yes	$(-0.117 \times \text{WS}) + (0.001 \times \text{Ht}) + 0.355$	0.68	0.47	0.45	0.000
Walking speed (m/s)	No	$(-1.542 \times \text{AHL}_{\text{sitting}}) + 1.869$	0.34	0.12	0.10	0.010

Wt, weight in N; WS, walking speed in m/s; Ht, height in cm; AHL_{sitting}, arch height index during sitting.

Table 2

Plantar pressure parameter model summary.

Dependent variable	Multivariate stepwise regression model	R	R ²	Adj R ²	Sig. F change
PP (N/cm ²)					
Hallux	$(2.739 \times \text{FFRF}) + 32.260$	0.44	0.19	0.18	0.001
Toe2	$(-84.110 \times \text{AHI}_{\text{Standing}} + (18.585 \times \text{WS}) - (0.219 \times \text{Ht}) + 59.597$	0.59	0.35	0.31	0.029
Toes3-5	$(-54.579 \times \text{AHI}_{\text{Standing}}) + 30.295$	0.45	0.20	0.18	0.001
MH1	$(-0.322 \times \text{TA} + (36.664 \times \text{WS}) + (110.631 \times \text{AHI}_{\text{Standing}}) - 14.973$	0.55	0.30	0.26	0.043
MH2	$(1.616 \times \text{FFRF}) + 36.369$	0.32	0.10	0.09	0.018
MH3	$(0.171 \times \text{TA}) + 15.431$	0.38	0.14	0.13	0.028
MH4	$(0.453 \times \text{Ht}) - 50.561$	0.56	0.32	0.30	0.000
MH5	$(0.460 \times \text{Ht}) - 52.859$	0.29	0.09	0.07	0.033
Medial arch	$(0.107 \times \text{TA}) + (64.725 \times \text{AHI}_{\text{Sitting}}) - (0.102 \times \text{Age}) + (0.459 \times \text{FFRF}) - 25.491$	0.72	0.51	0.47	0.025
Lateral arch	$(0.132 \times \text{TA}) + (36.764 \times \text{AHI}_{\text{Sitting}}) - (0.111 \times \text{Age}) - (14.679$	0.71	0.50	0.47	0.004
Medial heel	$(27.346 \times \text{WS}) + 3.111$	0.32	0.11	0.09	0.018
Lateral heel	$(34.729 \times \text{WS}) - (1.046 \times \text{FFRF}) - 6.282$	0.55	0.30	0.27	0.019
Total	$(33.004 \times \text{WS}) + 17.779$	0.34	0.12	0.10	0.012
MH1/MH2	$(-0.012 \times \text{TA}) + (3.227 \times \text{AHI}_{\text{Standing}}) + 1.127$	0.51	0.26	0.23	0.035
Hallux/MH1	$(0.055 \times \text{MVI}) + (0.11 \times \text{TA}) - 0.457$	0.51	0.26	0.23	0.004
CPEI (%)	$(1.207 \times \text{RCSP}) + (0.131 \times \text{TA}) + 9.055$	0.61	0.37	0.35	0.001

PP, peak pressure; FFRF, forefoot to rearfoot angle in °; AHI_{standing}, arch height index during standing; WS, walking speed; Ht, height in cm; MH, metatarsal head; TA, total area in cm²; AHI_{sitting}, arch height index during sitting; MVI, malleolar valgus index; CPEI, center of pressure excursion index in %; RCSP, resting calcaneal stance position in °.

Table 3

Maximum force parameter model summary.

Dependent variable	Multivariate stepwise regression model	R	R ²	Adj R ²	Sig. F change
MF (N)					
Hallux	$(6.968 \times \text{FFRF}) + 96.474$	0.42	0.18	0.16	0.002
Toe2	$(1.961 \times \text{FFRF}) + 15.990$	0.47	0.22	0.21	0.000
Toes3-5	$(-115.104 \times \text{AHI}_{\text{standing}}) + (29.682 \times \text{WS}) + 25.575$	0.45	0.20	0.17	0.024
MH1	$(815.63 \times \text{AHI}_{\text{standing}}) + (1.544 \times \text{Ht}) + (5.399 \times \text{FFRF}) - 419.796$	0.61	0.37	0.33	0.048
MH2	$(0.845 \times \text{TA}) + (1.1 \times \text{Ht}) - 128.513$	0.62	0.38	0.36	0.018
MH3	$(0.975 \times \text{TA}) + (1.384 \times \text{Ht}) - (62.618 \times \text{WS}) - 113.625$	0.73	0.53	0.50	0.018
MH4	$(0.803 \times \text{TA}) + (1.597 \times \text{Ht}) - (62.688 \times \text{WS}) - 182.082$	0.72	0.51	0.48	0.018
MH5	$(1.369 \times \text{Ht}) + (213.130 \times \text{AHI}_{\text{sitting}}) - 170.687$	0.53	0.28	0.25	0.037
Medial arch	$(0.53 \times \text{TA}) - (0.431 \times \text{Ht}) + 25.869$	0.62	0.39	0.36	0.016
Lateral arch	$(2.496 \times \text{TA}) - 205.222$	0.77	0.59	0.58	0.000
Medial heel	$(2.882 \times \text{Ht}) - 234.333$	0.61	0.37	0.36	0.000
Lateral heel	$(2.172 \times \text{Ht}) - 150.930$	0.50	0.25	0.23	0.000
Total	$(3.086 \times \text{TA}) + (6.224 \times \text{Ht}) + (1530.055 \times \text{AHI}_{\text{sitting}}) + (13.043 \times \text{FFRF}) - 319.403$	0.82	0.67	0.64	0.017
MH1/MH2	$(-0.007 \times \text{TA}) + (2.990 \times \text{AHI}_{\text{sitting}}) + 0.637$	0.45	0.20	0.17	0.047
Hallux/MH1	$(0.036 \times \text{MVI}) + 0.503$	0.41	0.17	0.15	0.002

MF, maximum force; FFRF, forefoot to rearfoot angle in °; AHI_{standing}, arch height index during standing; TA, total area in cm²; Ht, height in cm; AHI_{sitting}, arch height index during sitting; WS, walking speed in m/s; MVI, malleolar valgus index.