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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 GaitMat II gait pattern measurement system, and a goniometer. 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 pair wise 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 hind foot 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

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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 $\geq 4^\circ$ valgus OR FF-RF $\geq 4^\circ$ varus
- rectus: $0^\circ \leq$ RCSP $\leq 2^\circ$ valgus AND $0^\circ \leq$ FF-RF $\leq 4^\circ$ varus
- cavus: RCSP $\geq 0^\circ$ varus AND FF-RF $\geq 1^\circ$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:

$$\mathrm{AHF} = \frac{(\mathrm{AH}_{\mathrm{standing}} - \mathrm{AH}_{\mathrm{sitting}})}{0.4 \times \mathrm{BW}} \times 100 \quad (1)$$

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.

2.3.1. Plantar loading parameters

Each individual walked across anemed-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 (N s/cm^2) and normalized by total PTI.

Force-time integral, FTI, was calculated as absolute values (N s) and normalized by total FTI.

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

2.3.2. Gait pattern parameters

Each participant walked across a 7.32mGaitMatIIsystem (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, $\mathrm{AHI}_{\mathrm{sitting}}$, $\mathrm{AHI}_{\mathrm{standing}}$, 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.