INTRODUCTION

The basic concept of a foot type (e.g. Pes Planus, Rectus and Pes Cavus) refers to the structural organization of the human foot. While, the complexity of the foot (28 bones, 36 joints, and 112 ligaments) is generally appreciated by most clinical health care professionals its precise function is still not completely understood. In specific, how one foot type differs in function from another has not been comprehensively studied. Significant variation in the anatomical structure of human feet has been reported. These architectural variations are referred to as foot types. Root, Orien, and Weed suggest that foot alignment (architecture) determines biomechanical function. Individuals with a pes planus foot type are believed to hyperpronate in contact phase and remain maximally pronated throughout stance phase. In contrast, the rectus foot type is considered to exhibit initial pronation to promote shock absorption at heel strike followed by resupination in the midstance and propulsion phases. A number of objective measures of foot function have emerged in the past decade. The purpose of this study is to: (1) examine the differences in static and dynamic foot function between rectus and pes planus feet, (2) examine the relationship between static and dynamic foot function, and (3) enhance a multivariate model for discriminating pes rectus and planus foot types. It has been postulated that foot alignment (architecture) determines biomechanical function. Abnormal foot architecture has associated lower extremity soft tissue, joint, and skeletal positional malalignments that effect foot function. Patients who present with hyperpronated feet most often suffer from abnormal plantar pressure patterns, overuse injuries, knee-related injuries, structural deformities as well as arthritis and joint instability. It is not clear why one pes planus patient develops plantar fasciitis, one develops hallux abducto valgus, and another develops hallux limitus.

In 1996, Song et al. studied individuals with rectus (n=11) and pes planus (n=10) foot types. Each subject was evaluated in quiet standing with the malleolar valgus index (MVI) to assess static foot alignment and during comfortable cadence locomotion to assess dynamic foot function (CPEI) in the barefoot condition. The results demonstrated 100% correct classification of pes planus and 91% correct classification of rectus foot types. Although CPEI (a measure of the concavity of the center of pressure throughout stance phase) is considered a dynamic assessment it does not specify what angular excursions and translations the hindfoot elicited during gait.

In 1997, Liu et al. developed a technique to measure the unconstrained, six degree of freedom motions of the hindfoot. The resulting motions, based upon a floating axis type joint coordinate system, were described as three angular rotations (α, β, γ) and three linear displacements (q1, q2, and q3). Ten healthy individuals were tested and normative rotation and translation motions were described.

In 1997, Liu et al. developed a technique to measure the unconstrained, six degree of freedom motions of the hindfoot. The resulting motions, based upon a floating axis type joint coordinate system, were described as three angular rotations (α, β, γ) and three linear displacements (q1, q2, and q3). Ten healthy individuals were tested and normative rotation and translation motions were described.

Substantial variability was found in these parameters across the ten subjects possibly due to their different foot types. Unfortunately this study did not differentiate the foot types included in the results.

In 2002, Cornwall and McPoil presented kinematic results from 153 subjects. The hindfoot angular excursions were presented as single mean curves +/- one standard deviation. There was no subgrouping of the data according to foot type nor there were any translations reported. In 2003, Cornwall and McPoil presented the reliability and validity for two center of pressure quantification methods (i.e. lateral-medial area index and the lateral-medial force index). They utilized 105 subjects for the reliability study and a subset of 30 subjects to assess the frontal plane rearfoot eversion during the stance phase of walking. The investigators found that the center of pressure measures may have adequate between trial reliability measures but were not related to the magnitude of frontal plane rearfoot eversion. There was no subgrouping of the data according to foot type nor there were any translations reported.

METHODS

The following instrumentation from the Gait Study Center (GSC) at the Temple University School of Podiatric Medicine (TUSPM) were used in this investigation:
- A standard goniometer (1° resolution) - to measure foot positioning during the clinical biomechanical exam. Parameters such as Resting Calcaneal Stance Position (RCSP), Neutral Calcaneal Stance Position (NCSP), Sub-Talar Joint Neutral Position, and Forefoot to Rearfoot relationship (FF-RF) were used for the subjects’ foot type pre-classification.
- A flatbed Microtek Scanner - to collect the data necessary to calculate the Malleolar Valgus Index (MVI). MVI is determined from a scanned image of the foot in resting calcaneal stance position. The subject is asked to stand on a 7/8” thick plexiglass platform that was placed over the flatbed scanner. The accompanying MVI jig is adjusted to snugly fit about the transmalleolar axis and determine the position of the medial and lateral malleoli. (Figure 1)
the plantar foot is scanned the position of the malleoli is captured and registered with respect to the transverse plane image of the foot.

MVI is defined as the deviation from the midpoint of the transmalleolar axis to the midpoint of the hindfoot in the transverse plane normalized to ankle width. MVI is calculated using the following formula:

$$\text{MVI} = \left[ \frac{\text{LA} - \text{LF}}{\text{LM}} \right] \times 100\%$$

LA - distance between the calculated position of the lateral malleolus and the transmalleolar axis bisection
LF - distance between the calculated position of the lateral malleolus and the foot bisection
LM - distance between the calculated position of the lateral and medial malleoli.

- A tachometer - to record the average speed of each trial during gait. This system is comprised of a light interrupt-based timing circuit. As the subject traverses the walkway, one interrupts a mid-thigh level photoelectric beam that initiates a timer. The subject trips a second photoelectric beam located 4 meters away, which stops the timer. The average velocity is then computed and displayed. It is well known that most gait parameters are a function of average velocity or walking speed. In this sense, the average velocity is an important covariate in the statistical analysis.

- The Musgrave Footprint™ pressure plate is a platform-based vertical pressure measurement system that is mounted flush within the 52’ walkway at the GSC. Pressure is measured by an array of 2048 force sensitive resistor (FSR) sensors that are sampled at approximately 60 Hz. Each FSR has a surface area of 0.25 cm$^2$ and can record pressure from 0 to 15 kg/cm$^2$ during posture or comfortable cadence locomotion. (Figure 2) Plantar pressures in excess of 10 kg/cm$^2$ during comfortable cadence locomotion are considered pathologic. These data (in particular CPEI) are collected and analyzed on a Pentium II 400Mhz IBM compatible computer. Center pressure excursion index (CPEI) is a measure of the concavity of the center of pressure curve.

A group of 10 healthy volunteers between the ages of 20 and 28 who could ambulate without assistance was recruited for this pilot study. Five subjects (9 feet) had a flexible pes planus foot type ($\geq 4^\circ$ everted resting calcaneal stance position (RCSP) and $> 4^\circ$ inverted forefoot to rearfoot relationship (FF-RF)). Five subjects (8 feet) had a rectus foot type (RCSP $\leq 2^\circ$ varus or valgus and a FF-RF $\geq 0^\circ$ and $\leq 4^\circ$ varus). All participating volunteers had to meet the following exclusion criteria such as: history of neuro-muscular and musculo-skeletal diseases, limb length discrepancy (>1cm), prior joint fusions in the skeletal system (especially lower extremity), and gross stiffness or laxity (i.e. Marfan’s Disease, Tarsal coalition, Ehlers-Danlos Syndrome, etc.). Each subject’s visit consisted of a lower extremity clinical examination, a static postural assessment, and a dynamic gait analysis in the barefoot condition. Static hindfoot alignment was captured with the Malleolar Valgus Index (MVI) jig. Dynamic foot function was assessed using the Musgrave Footprint™ pressure plate for CPEI measurements and the Vicon™ 370 motion analysis system for six-degree-of-freedom hindfoot kinematics during gait. Each subject was asked to ambulate across the walkway at their self-selected walking speed; plantar pressure, motion data and average velocity were collected concurrently utilizing the Musgrave Footprint™, Vicon 370™ and tachometer respectively. Three trials were collected in the barefoot condition for each limb for each type of data.

![Figure 2: Center of Pressure Excursion Index](image)

- The Vicon 370™ is a self-contained 3D motion analysis system. The system tracks the trajectories of a large number of retro-reflective markers placed upon anatomical bony landmarks in the field-of-view (1m x 1m x 0.5m). Figure 3 The Vicon 370™ software resides in both the data and workstations. A single interactive program on the workstation controls data capture and upload, 3D photogrammetric calibration, automatic 3D reconstruction, and display of results. In this study the Vicon 370™ generated the 3D marker coordinates for a custom written program to quantify six degree of freedom kinematics of the hindfoot by constructing embedded coordinate systems within the tibia and calcaneus.

![Figure 3: Retroreflective Marker Set](image)
RESULTS AND DISCUSSION

Eversion and medial-lateral translation are shown in figure 4. Curves are generated for rectus, planus, and all feet. As shown in Table I univariate analysis of variance type models were employed to assess the differences in MVI, CPEI, Peak Eversion, and Peak Medial Translation. Group means (standard deviations) and the corresponding P values are summarized. Significant differences between rectus and planus foot types were obtained for MVI and CPEI. Peak eversion was nearly significant across foot types (P=0.059). This comparison was probably hampered by the small group sizes. Peak medial translation was not significantly different across foot types.

To examine the potential relationships between static and dynamic measures of foot function univariate and multivariate correlation analyses were performed. Static foot function as measured by MVI was negatively correlated (R=-0.784) with dynamic foot function as measured by CPEI but not with medial translation (R=0.104). A weak correlation was observed between CPEI and peak eversion (R=0.403). This is not surprising since eversion is derived from tibio-calcaneal motion in the frontal plane while CPEI is derived from loading beneath the hindfoot, midfoot, and forefoot. Peak eversion was uncorrelated with peak medial translation (R=-0.187). Static and dynamic foot function does not appear to be highly correlated in a multivariate sense (Table 2). A multivariate regression model was constructed to estimate CPEI from MVI, peak eversion, and peak medial translation. This relationship was essentially unchanged by including the kinematic parameters (R=0.785).

Table 2: Static and dynamic foot function

<table>
<thead>
<tr>
<th>CPEI</th>
<th>MVI</th>
<th>Peak Evers.</th>
<th>Peak Med. Trans.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPEI</td>
<td>1</td>
<td>-.784</td>
<td>.403</td>
</tr>
<tr>
<td>MVI</td>
<td>-.784</td>
<td>1</td>
<td>-.533</td>
</tr>
<tr>
<td>Peak Eversion</td>
<td>.403</td>
<td>-.533</td>
<td>1</td>
</tr>
<tr>
<td>Peak Med. Trans.</td>
<td>.104</td>
<td>-.087</td>
<td>-.187</td>
</tr>
</tbody>
</table>

A multivariate analysis of variance model (MANOVA) was constructed with CPEI, MVI, and peak eversion stratified by foot type. A linear discriminant function was established which resulted in 100% correct classification of pes planus and rectus foot types with or without peak eversion. The inclusion of the peak eversion parameter may improve classification in future studies where other foot types (e.g. pes cavus) and pathological conditions are included.

SUMMARY

The investigators examined the relationship between static and dynamic foot function and found a good correlation between MVI and CPEI. The correlation between peak eversion and CPEI was considered weak. Finally adding peak eversion to the feature space, which includes MVI and CPEI, for discriminating pes rectus and planus foot types did not enhance model foot type prediction performance.

REFERENCES


ACKNOWLEDGEMENTS

Kristy Richards, M.S. Chief Engineer, Gait Study Center
Jim Shipley, 3rd year TUSPM student
Figure 4a – Eversion for all feet (n=17)

Figure 4b – Eversion for rectus feet (n=8)

Figure 4c – Eversion for planus feet (n=9)

Figure 4d – Lat.-Med. Translation for all feet (n=17)

Figure 4e – Lat.-Med. Translation for rectus feet (n=8)

Figure 4f – Lat.-Med. Translation for planus feet (n=9)