Session 7: Foot Type I

Co-Moderators: Jinsup Song, PDM, PhD (TUSPM) and Robert Turner, PT, DPT (HSS)

9:00AM  7-1: Fields, Cheryl, et al. Foot Structure, Function, and Flexibility in MS Patients


9:20AM  7-3: Krzak, Joseph J., et al. Foot posture is associated with plantar pressure during gait: a comparison of normal, planus and cavus feet

9:30AM  7-4: Olsen, Mark T., et al. Static Foot Structure May Predict Midfoot Mechanics


9:50PM  7-6: Roberts, Lauren, et al. WBCT Hindfoot Alignment of Adult Acquired Flatfoot Deformity: A Comparison of Clinical Assessment and Weightbearing ConeBeam CT Examinations

10:00AM  7-7: Michael Rainbow, et al. In Vivo Intrinsic Foot Bone Motion Measured with Bead Tracked Biplanar Videoradiography
Foot Structure, Function, and Flexibility in MS Patients

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INTRODUCTION: Multiple Sclerosis (MS) is a progressive inflammatory neurologic condition common in young adults with a high prevalence of unsteady gait and balance resulting in frequent falls. Since the foot is the first structure to interface with the ground and help support our mass during gait and posture and many of these patients have different degrees of drop foot, our goal of this cross-sectional pilot study was to characterize foot structure, function, and flexibility in those suffering from MS.

METHODS: The study population included 53 MS patients and 19 healthy controls each of who underwent four sets of measurements. Foot structure was measured using Arch Height Index (AHI) device (JAK Tool, Cranbury, NJ) and participants were classified into planus, rectus, or cavus feet. Function was assessed by measuring the center of pressure excursion index (CPEI) during gait at one’s self-selected walking speed using a plantar pressure measuring device (emem-X, Novel electronics, St Paul, Mn.). Secondary function analyses were performed on masked regions of the maximum plantar loading (ie pressure, force) throughout stance phase plot. Flexibility was assessed by calculating arch height flexibility (AHF) from sitting and standing AHI measurements. All participants had a timed 25 foot walk test.

RESULTS: MS patients (x=6.8s, s=4.98s) required significantly (p=0.0036) longer times to walk 25 feet than controls (x=4.53s, s=4.45s). Foot structure was planus in arch height and not significantly different between MS and control subjects. MS subjects differed in foot function as evidenced by a great pressure time integral (PTI), force time integral (FTI), contact area, and maximum force beneath the medial arch compared with controls during self-selected walking speed. MS subjects had a lower pronation supination index in midstance and early midstance indicative of over-pronation. In addition the MS subjects had lower maximum force and peak pressure under the 2nd metatarsal head compared with controls during gait. Although the MS subjects exhibited greater AHF this difference was not significant.

DISCUSSION: The findings support the postulate that MS patients have a planus foot structure that exhibit more over-pronation during gait than controls. MS subjects had higher 1st met head forces and pressures and lower 2nd met head forces and pressures than control subjects. Controls in this study had a lower 1st met head pressure and higher 2nd suggesting a hypermobile 1st ray as was seen in Hillstrom et al (2013). MS subjects had a different distribution with 1st met head forces and pressures similar to that of the 2nd met head. This unique pressure distribution in MS subjects may be a compensation for balance and proprioception deficits. By keeping the first metatarsal head firmly on the ground may provide greater sensory feedback and improve compromised gait and posture but this theory would need further testing.

SIGNIFICANCE/CLINICAL RELEVANCE: Understanding the differences in foot structure, function, and flexibility could enhance the therapeutic strategies for decreasing the risk of falls in MS patients. The more medially directed loading associated with the over-pronating foot may pre-dispose the MS patient to secondary pedal pathologies (e.g. hallux rigidus, hallux valgus, posterior tibial dysfunction, and Achilles tendonitis).

REFERENCES:
Introduction: Previous work has demonstrated that the amount of radiographic hindfoot correction required at the time of adult acquired flatfoot deformity (AAFD) surgical treatment can be predicted by the amount of radiographic deformity present before surgery. Successful outcomes after reconstruction are closely correlated with hindfoot valgus correction. However, it is not clear if differences exist between clinical and radiographic assessment of hindfoot valgus. The purpose of this study was to evaluate the correlation between radiographic and clinical evaluation of hindfoot alignment in patients with stage II AAFD.

Methods: Twenty-nine patients (30 feet) with stage II AAFD, 17 men and 12 women, mean age of 51 (range, 20 to 71) years, were prospectively recruited. In a controlled and standardized fashion, bilateral weightbearing radiographic hindfoot alignment views were taken. Radiographic parameters were measured by two blinded and independent readers: hindfoot alignment angle (HAA) and hindfoot moment arm (HMA). Clinical photographs of hindfoot alignment were taken, in three different vertical camera angulations (0, 20 and 40 degrees). Pictures were assessed by the same readers for standing tibiocalcaneal angle (STCA) and resting calcaneal stance position (RCSP). Intra- and interobserver reliability were assessed by Pearson/Spearman’s and intraclass correlation coefficient (ICC), respectively. Relationship between clinical and radiographic hindfoot alignment was evaluated by a linear regression model. Comparison between the different angles (RCSP, STCA and HAA) was performed using Wilcoxon rank sum test. P-values of less than 0.05 were considered significant.

Results: We found overall almost perfect intra- (range, 0.91-0.99) and interobserver reliability (range, 0.74-0.98) for all measures. Mean value and confidence interval (CI) for RCSP and STCA were 10.78 degrees (CI: 10.09-11.47) and 12.55 degrees (CI: 11.71-13.40), respectively. The position of the camera did not influence readings of clinical alignment (p>.05). The mean HMA was 18.74mm (CI: 16.34-21.14mm) and the mean HAA was 23.54 degrees (CI: 21.08-25.99). Clinical and radiographic hindfoot alignment were found to significantly correlate (p<.05). However, the radiographic hindfoot alignment (HAA) demonstrated increased valgus when compared to both clinical alignment measurements, with a mean difference of 12.76 degrees from the RCSP (CI: 10.99-14.53, p<.0001) and 10.98 degrees from the STCA (CI: 9.22-12.76, p<.0001).

Conclusion: We found significant correlation between radiographic and clinical hindfoot alignment in patients with stage II AAFD. However, radiographic measurements of hindfoot alignment angle demonstrated significantly more pronounced valgus alignment than the clinical evaluation.

Clinical Relevance: The results of our study suggest that clinical evaluation of hindfoot alignment in patients with AAFD potentially underestimates the bony valgus deformity. One should consider these findings when using clinical evaluation in the surgical treatment algorithm for flatfoot patients.
Foot posture is associated with plantar pressure during gait: a comparison of normal, planus and cavus feet

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Disclosures: the authors have none to declare.

INTRODUCTION: The aim of this study was to compare plantar pressure between healthy individuals with normal, planus or cavus feet.

METHODS: Ninety-two healthy volunteers (aged 18 to 45) were classified as either normal (n=35), pes planus (n=31) or pes cavus (n=26) based on the Foot Posture Index, Arch Index and normalised navicular height truncated. Barefoot walking trials were conducted using an emed\textsuperscript{\textregistered} x400 plantar pressure system (Novel GmbH, Munich, Germany). A 10 region mask was used that included the heel, midfoot, 1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd}, 4\textsuperscript{th} and 5\textsuperscript{th} metatarsophalangeal joints, hallux, 2\textsuperscript{nd} toe, and the 3\textsuperscript{rd}, 4\textsuperscript{th} and 5\textsuperscript{th} toes. Peak pressure, pressure-time integral, maximum force, force-time integral and contact area were calculated for each region. To test for differences between groups, a one-way analysis of variance (ANOVA) was performed with significance level set at <0.05. Post-hoc comparisons of the mean differences (MD) between groups with Bonferroni adjustments were applied to all ANOVAs. Confidence intervals (CI) and effect sizes (ES) using Cohen’s d were calculated for all significant mean differences.

RESULTS: Overall, the largest differences were between the planus and cavus foot groups in forefoot pressure and force. In particular, peak pressures at the 4\textsuperscript{th} and 5\textsuperscript{th} metatarsophalangeal joints in the planus foot group were lower compared to the normal and cavus foot groups, and displayed the largest effect sizes (Figure 1). The cavus group demonstrated higher peak plantar pressure in the heel compared the planus group, and in the 1st MTPJ compared to both the normal and planus groups.

DISCUSSION: The findings from this study indicate that the largest difference between foot posture groups, both in the number of significant post-hoc comparisons and the magnitude of effect size, was between planus and cavus feet, mostly in the lateral and medial regions of the forefoot.

SIGNIFICANCE/CLINICAL RELEVANCE: This study confirms that foot posture does influence plantar pressures, and that each foot posture classification displays unique plantar pressure characteristics.

ACKNOWLEDGEMENTS: The data for this study was collected by AKB during his doctoral studies, which were funded by the Australian Government. In addition, HBM is currently a National Health and Medical Research Council Senior Research Fellow (ID: 1020925).

\textbf{Figure 1.} Peak pressure diagrams for all foot posture groups (top) and differences in peak pressure for all foot posture group comparisons (bottom). For the foot posture comparison diagrams, red indicates greater peak plantar pressure values and blue indicates lesser peak plantar pressure values.
Static Foot Structure May Predict Midfoot Mechanics

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INTRODUCTION: Clinical interventions for foot injury rehabilitation and prevention are often prescribed based on static measures of foot structure. However, this convention merits further investigation as the static-dynamic relationship has only been explored in walking and running and remains unclear in the literature. As such, a drop landing task may be a valuable mechanism to apply a greater stress to the foot to uncover a static-dynamic relationship. Therefore, the primary aim of this study was to explore the relationship between static foot structure and dynamic midfoot kinematics and kinetics during a barefoot single-leg landing.

METHODS: Forty-eight females (age = 20.4 ± 1.8 yr, height = 1.6 ± 0.06 m, weight = 57.3 ± 5.5 kg) signed an informed consent approved by the institutional review board before participating in this cross-sectional study. Static foot structure of the dominant leg was measured using the Arch Height Index Measurement System (AHIMS). Standing arch height index (AHI) was calculated as dorsum height divided by truncated foot length. Skin surface markers were attached to the dominant leg and foot according to a multi-segment foot model created by Bruening et al.1 A14-camera motion capture system (Vicon, Motion Capture Systems, Ltd.) was used to sample kinematic data at 250 Hz while 2 force platforms (Advanced Mechanical Technology, Inc.) were used to collect kinetic data at 1000 Hz. A static trial was captured with subjects in equal weight-bearing stance. Subjects then hung from wooden rings and performed barefoot single-leg drop landings onto 2 force platforms from a height of 0.4 m. A successful trial constituted a natural landing in which the navicular and cuboid markers aligned with the split between the 2 forces platforms, resulting in a rear foot and forefoot impact on separate plates. Data from the landing trials were imported into Visual 3D (C-motion, Inc.) for calculation of static midfoot angle (MA), midtarsal range of motion (ROM), and midtarsal work. Pearson correlation coefficients were calculated for static and dynamic variables using paired t-tests in SAS (SAS Institute, Inc.).

RESULTS: A significant inverse correlation was found between standing AHI using AHIMS and static MA using motion capture technology (r = -0.6087, p < 0.0001). Standing AHI was correlated negatively with sagittal plane midtarsal ROM (r = -0.32032, p = 0.0264) and positively with midtarsal work (r = 0.33180, p = 0.0212). Static MA was correlated positively with sagittal plane midtarsal ROM (r = 0.48336, p = 0.0005) and negatively with midtarsal work (r = -0.32321, p = 0.0250). Raw data can be referenced in Table 1.

DISCUSSION: The strong inverse correlation between the standing AHI and static MA suggests that either method is appropriate for characterizing static foot structure in clinical and research settings. However, static MA showed a stronger correlation to sagittal plane midtarsal ROM than standing AHI. When comparing static and dynamic foot measures, it may be beneficial to use the same technology to reveal any existing relationships that are present. We also found a relationship between both static foot structure measures and both midtarsal ROM and midtarsal work. More specifically, we observed that static foot structure was able to predict 31-48% of variation associated with dynamic midfoot function during a landing task. Our findings suggest that midfoot function may be predictable without having to administer dynamic testing accompanied by complex collection processes and analyses. However, a higher impact dynamic task, such as a drop landing, may required to properly observe a static-dynamic relationship. This type of landing could be performed clinically using a 2D high speed video camera and skin surface markers. We used a multi-segment foot model to measure midtarsal ROM, which is an improvement from traditional models but is still limited in identifying individual tarsal articulations.

SIGNIFICANCE/CLINICAL RELEVANCE: Static foot structure may be a valuable clinical tool in assessing midfoot function relating to injury risk in athletes, who participate in high impact, repeated loading activities, as well as in pathological populations.


FIGURES AND TABLES:

Table 1 Raw data for static and dynamic variables

<table>
<thead>
<tr>
<th>Standing AHI</th>
<th>Static MA (deg)</th>
<th>Midtarsal ROM (deg)</th>
<th>Midtarsal Work (J·kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SD</td>
<td>0.324 ± 0.019</td>
<td>-22.475 ± 5.229</td>
<td>27.041 ± 6.916</td>
</tr>
</tbody>
</table>
**Measurement of Foot Muscle Strength and Activation**

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**INTRODUCTION:** Intrinsic and extrinsic foot muscles play an important role in proper foot function, yet functional methods of quantifying foot muscle strength are not readily available for clinicians and researchers. Understanding if weakness is present may influence injury prevention and/or rehabilitation efforts. While some functional movements that can isolate the foot muscles are habitual for most adults (toe flexion), others are unfamiliar (doming or short-foot) and may require training to get a reliable measurement. Therefore, the purpose of this study was multi-factorial: 1) to measure the reliability of two methods of measuring foot strength during doming, 2) to determine if there was a learning effect when testing unfamiliar movements, and 3) to measure foot muscle activity during each test.

**METHODS:** Forty-five subjects (21 M, 24 F; age 25.2±6.4 y; ht 171.5±10.1 cm; wt 71.0±13.1 kg) signed IRB approved consent forms, then completed 2 testing sessions, 2 weeks apart. During each testing session, subjects completed 3 trials of the following tests, in random order: Doming-pull (DL), Doming-push (DS), Great toe flexion (GT), and Lateral toes flexion (LT). DL and DS required the same movement, but the force transducer was secured below the foot during DL and above the foot during DS. Surface EMG data was collected from the gastrocnemius (GAS), fibularis longus (FL), fibularis brevis (FB), tibialis anterior (TA), and abductor hallucis (ABDH). EMG data were normalized to muscle activity during weight-bearing maximal plantarflexion (GAS, FL, FB, and ABDH) or maximal dorsiflexion (TA). During the 2 weeks between testing sessions, subjects were asked to practice the doming movement daily.

Force and EMG data were synchronized and averaged over 1000 points (force = 1000 Hz, EMG = 2000 Hz) surrounding peak force. Within day reliability of the doming strength measurements was assessed using interclass correlation coefficients (ICC2,k) across the three trials. Differences between doming strength during the two sessions were assessed using paired t-tests. A 2-way ANOVA determined differences in percentage of muscle activation between tests during Day 2 testing.

**RESULTS:** Within session reliability of DL and DS were good-excellent for the first and second days (Table 1). Strength increased between days for both devices (p≤.003). Muscle activity (Table 2) in the GAS was not significantly different between any of the exercises. The FL, FB, TA, and ABDH showed significantly more activity during DL and DS compared to GT and LT (p≤.01). The ABDH was activated significantly more than the other muscles during DL, DS, and GT (p≤.002).

**DISCUSSION:** Within session reliability of DL and DS were comparable and the strength measurements were strongly correlated (r=0.8), indicating that either method could be used. Comparing doming strength measurements between days, it appears that either a learning effect or strengthening during the 2 weeks of practice allowed subjects to produce more force during Day 2. The increased reliability of the DS measurement on Day 2 suggests less variation between trials per subject.

Muscle activity was normalized to a submaximal contraction, which represents a limitation of the study, but still allows for an indication of which muscles are being used to perform the doming and toe flexion actions. These tests are conducted to try to isolate intrinsic foot muscles, while minimizing the activity of the associated extrinsic muscles. Our data showed that the ABDH is activated during all of the movements we tested. Interestingly, it was more active during DL than DS, though not statistically significant. Force output was also greater in the DL than DS (p<.001).

**SIGNIFICANCE/CLINICAL RELEVANCE:** These tests are reliable for measuring foot muscle strength. Due to the apparent learning effect, subjects or patients should be taught the doming movement prior to testing.

**FIGURES AND TABLES:**

Table 1. Force (avg ± SD) for doming tests.  

<table>
<thead>
<tr>
<th></th>
<th>DL (lbf)</th>
<th>ICC</th>
<th>DS (lbf)</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>24.7±13.2</td>
<td>0.937</td>
<td>20.4±6.2</td>
<td>0.866</td>
</tr>
<tr>
<td>Day 2</td>
<td>33.5±16.6</td>
<td>0.962</td>
<td>24.9±6.2</td>
<td>0.948</td>
</tr>
<tr>
<td>% change</td>
<td>+34.4</td>
<td></td>
<td>+22.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Percent activation for each muscle during each test on Day 2 (avg ± SD), represented as a percentage of muscle activation during weight-bearing plantarflexion (GAS, FL, FB, and ABDH) or dorsiflexion (TA).

<table>
<thead>
<tr>
<th></th>
<th>GAS</th>
<th>FL</th>
<th>FB</th>
<th>TA</th>
<th>ABDH</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL</td>
<td>7.79±4.34</td>
<td>39.1±23.0</td>
<td>46.9±30.4</td>
<td>45.8±27.2</td>
<td>94.3±66.1</td>
</tr>
<tr>
<td>DS</td>
<td>7.38±4.64</td>
<td>38.0±25.4</td>
<td>42.3±28.9</td>
<td>40.9±22.9</td>
<td>78.9±69.4</td>
</tr>
<tr>
<td>GT</td>
<td>7.94±6.47</td>
<td>12.8±8.23</td>
<td>19.0±8.42</td>
<td>20.8±13.3</td>
<td>32.2±29.4</td>
</tr>
<tr>
<td>LT</td>
<td>10.1±8.64</td>
<td>13.0±9.21</td>
<td>25.4±13.8</td>
<td>27.2±18.9</td>
<td>25.8±22.7</td>
</tr>
</tbody>
</table>
WBCT Hindfoot Alignment of Adult Acquired Flatfoot Deformity: A Comparison of Clinical Assessment and Weightbearing ConeBeam CT Examinations

Lauren Roberts1, Cesar de Cesar Netto1, Scott Ellis1, Shadpour Demehri2, Lew Schon3

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Disclosures: No relevant disclosures.

INTRODUCTION:
Assessment of hindfoot alignment in adult acquired flatfoot deformity (AAFD) can be challenging. Clinical judgment and radiograph studies while important may not represent the accurate valgus alignment of the affected patients. Weightbearing (WB) ConeBeam CT (CBCT) is an emerging imaging modality that may potentially better demonstrate the three-dimensional (3D) deformity, facilitating visualization of important soft-tissue and bony landmarks and helping in surgical planning. Based on the relative position of bone and soft-tissue axes, different measurements of hindfoot alignment can be obtained with CT images. Therefore, we compared clinical assessment of hindfoot valgus alignment in AAFD patients with different measurements performed on WB CBCT images.

METHODS:
In this prospective, IRB-approved study, 20 patients (20 feet, 15 right and 5 left) with clinical diagnosis of flexible AAFD were included. There were 12 males and 8 females, with a mean age of 52.2 years (range, 20 – 88 years of age), and average BMI of 30.35 kg/m² (range, 19.00 – 46.09 kg/m²). Patients underwent “clinical” assessment of hindfoot alignment as well as WB CBCT. Two independent and blinded foot and ankle board-certified surgeons performed different hindfoot alignment measurements on the WB CBCT images that included: 3D “clinical” alignment using soft tissue axes of the tibia and calcaneus; Achilles tendon axis/calcaneal tuberosity angle; angles formed between the tibial axis and the calcaneal tuberosity, calcaneal axis and line connecting midpoint of subtalar joint and most inferior part of calcaneal tuberosity. Positive values were considered valgus alignment. Mean differences between the measurements modalities were compared by paired T-test. Intra- and Inter-observer reliability for the WB CBCT measurements were calculated using Pearson correlation.

RESULTS:
The mean clinical hindfoot valgus measured was 15.15° (SD 7.7°). It was found to be significantly different from the mean values of all WB CBCT angles modalities: 3D “clinical” alignment (10.42°, p<0.015); Achilles tendon/calcaneal tuberosity angle (2.96°, p<0.0001); tibial axis/calcaneal tuberosity angle (5.42°, p<0.0001); tibial axis/subtalar joint angle (7.52°, p<0.0001) and tibial axis/calcaneal axis angle (20.39°, p<0.017).

We found an excellent intra-observer agreement for all WB CBCT 3D measurements (range, 0.8863 – 0.9713, p<0.0001). There was also good to excellent inter-observer reliability, with the exception of the 3D “clinical” alignment (r=0.450, p<0.04), that showed moderate correlation.

CONCLUSIONS:
The use of 3D WB CBCT imaging can help characterize the valgus hindfoot alignment in patients with adult acquired flatfoot deformity. We found the different CBCT measurements modalities to be reliable and repeatable, and to significantly differ from the clinical evaluation of hindfoot valgus alignment.

SIGNIFICANCE/CLINICAL RELEVANCE:
Reliably characterizing hindfoot alignment is integral to surgical planning to ensure appropriate correction to obtain best possible patient outcomes.
In Vivo Intrinsic Foot Bone Motion Measured with Bead Tracked Biplanar Videoradiography

Michael J Rainbow¹, Lauren Welle¹, Andrew WL Dickinson¹, Toni Arndt²

Introduction: Three of the most ubiquitous models of foot function are the spring-arch [1], the windlass mechanism [2], and the transverse tarsal locking mechanism [3]. In recent years, some of these mechanisms have been revisited and refined. For example, Kelly et al. showed that the intrinsic foot muscles act on the arch more than previously thought [4], which calls into question the dominant role ascribed to the passive structures such as the plantar aponeurosis. Holowka et al. and others questioned the rigid lever concept by showing that the midtarsal joint is less stiff during push off than was previously assumed [5]. Likewise, Okita et al. found that the transverse tarsal joint moves throughout the gait cycle [6], which challenges the concept of the transverse tarsal locking mechanism. A mechanistic understanding of foot and ankle function is crucial because treatment strategies aim to restore or replace the foot’s versatile function; however, the current models seem to be insufficient and have not yet been replaced by a comprehensive unified model.

Two challenges in determining a unified theory of foot function are large inter-subject variability in the foot’s morphology, and difficulty in measuring the intricate motion of the foot bones during in vivo dynamic activities. X-ray Reconstruction of Moving Morphology (XROMM) is an emerging approach to measure in vivo foot and ankle bone motion during dynamic tasks; however, it remains challenging to track the foot bones with sufficient accuracy to analyze joint arthromechanics. The purpose of this study was to quantify intrinsic motion of the foot at high accuracy with a subject who had tantalum beads implanted into his foot bones. Here we report accuracy of scientific rotoscoping for markerless tracking, and we report preliminary results on the axes of rotation of the tarsus.

Methods: One male subject (49y) previously had a set of three tantalum beads implanted in the calcaneus, talus, navicular, cuboid, medial cuneiform, and first metatarsal (MT1). After ethics approval and informed consent, CT scans were acquired of the foot (0.441x0.441x0.625mm). The subject performed one-legged hopping at three frequencies (108/120/132 bpm). He also jogged slowly while barefoot. The beads were segmented in the CT scans (Mimics, Materialise) and tracked in XMA Lab (Brown University). The bones were segmented and registered to the beads. The bones were also tracked markerlessly using scientific rotoscoping in Autoscoper (Brown University). We computed RMS errors using the bead tracking as the gold standard. We also computed the instantaneous helical axis of motion and angular velocity of the medial longitudinal arch (MT1 wrt calcaneus), as well as the cuboid, navicular, and calcaneus relative to the talus.

Results and Discussion: RMS errors were small by motion capture standards but larger than previously reported tracking of isolated long bones (< 0.1 mm, 0.1 deg), and too large to generate stable instantaneous helical axes without taking larger steps (Table 1); therefore, manual rotoscopy techniques may not be adequate to establish a detailed understanding of joint velocities and accelerations, and these may be important for understanding how the foot manages loads. More robust global optimization may be required; for example, the simulated annealing 4D tracking algorithm implemented in DSX (C-Motion). Collision detection, multi-bone tracking, and model-based tracking may also be required.

The rotation axis of the medial longitudinal arch moved substantially in 3D from the navicular to the talar neck during weight acceptance and then moved back to the navicular during pushoff, indicating that the joints along the arch alter their relative contributions throughout the cycle. The cuboid, navicular, and calcaneus largely shared a common axis that swept through a range of 13 degrees throughout the cycle. Although the axes were similar, the amount of rotation of the talonavicular and cuboid navicular joint was up to 2.5 times larger than the sub talar joint. Given the unlikely scenario that only this specific subject possesses a single common axis at the tarsal complex, we hypothesize that some of the variation observed in foot bone morphology accommodates a single axis at the tarsal complex so that it can manage deceleration and acceleration of the talus during loading and propulsion.

Table 1: RMS errors between markerless and bead data across proximal tarsal joints.

<table>
<thead>
<tr>
<th>X_joints</th>
<th>Y_joints</th>
<th>Z_joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.65 ± 2.21°</td>
<td>3.12 ± 2.64°</td>
<td>2.40 ± 2.26°</td>
</tr>
</tbody>
</table>

Figure 1: Angular velocity and axis of rotation of the medial longitudinal arch (hopping).

Figure 2: Angular velocity during jogging of each joint in the talar coordinate system. A. Dorsiflexion B. Eversion C. Internal Rotation. D. Helical axes of the cuboid, navicular and calcaneus relative to the talus coordinate system during late stance.