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# Segmental foot mobility in individuals with and without diabetes and neuropathy

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**Abstract**

*Background.* Impairment in intrinsic foot mobility has been identified as an important potential contributor to altered foot function in individuals with diabetes mellitus and neuropathy, however the role of limited foot mobility in gait remains poorly understood. The purpose of our study was to examine segmental foot mobility during gait in subjects with and without diabetes and neuropathy.

*Methods.* Segmental foot mobility during gait was examined using a multi-segment kinematic foot model in subjects with diabetes ($n = 15$) and non-diabetic control subjects ($n = 15$).

*Findings.* Subjects with diabetes showed reduced frontal as well as sagittal plane excursion of the calcaneus relative to the tibia. Decreased excursion of the first metatarsal relative to the calcaneus in the frontal as well as transverse plane was noted in subjects with diabetes.

*Interpretation.* Our findings agree with traditional understanding of foot mechanics and shed new light on patterns and magnitude of motion during gait. Calcaneal pronation, noted in early stance in both groups, was reduced in subjects with diabetes and may have important consequences on joints proximal as well as distal to it. Subjects with diabetes showed reduced foot 'splay' in early stance, indicated by first metatarsal and forefoot eversion. At terminal stance, decreases in calcaneal plantarflexion, first metatarsal and forefoot supination were noted in subjects with diabetes, suggesting that less supination is required in subjects with diabetes to create a rigid lever. In subjects with diabetes, a greater proportion of midfoot stability may be derived from modified/stiffer soft tissue such as the plantar fascia.

*Keywords:* Diabetes; Foot mobility; Kinematic model

## 1. Introduction

Plantar ulcers develop in an estimated 15% of patients with diabetes mellitus (DM) (Gordois, 2003). Along with grave consequences in terms of health and functional abilities (Price, 2004; Mueller, 2004), foot ulcers and associated amputation are often harbingers of personal and financial hardships. Factors contributing to altered foot function and thus the development of foot ulcers are therefore of considerable interest.

Normal foot function during gait requires the foot to transition from a flexible structure that dissipates impact as it contacts the ground to a rigid structure that allows for efficient propulsion during push-off (Saltzman and Nawoczenski, 1995). To reconcile these widely divergent demands, the foot acts as a twisted osteo-ligamentous plate (Sarrafian, 1987), where calcaneal eversion is accompanied by unlocking of the midfoot and concomitant first ray dorsiflexion. Conversely, calcaneal inversion is accompanied by midfoot rigidity and first ray plantarflexion.

Impairments in intrinsic foot mobility have been identified as key factors underlying altered foot function in individuals with DM. Reduced subtalar joint mobility, specifically inadequate calcaneal eversion has been

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documented in subjects with DM (Arkkila et al., 1997; Delbridge et al., 1988; Duffin, 1999; Fernando, 1991; Fernando and Vernidharan, 1997; Frost and Beischer, 2001; Glasoe, 2004; Mueller, 1989). Reduced subtalar mobility may have significant biomechanical consequences (Rosenbaum, 1996; Sammarco, 2004) including increases in transverse tarsal joint rigidity predisposing to lateral column overweighting. Similarly, limited first metatarsal mobility (Glasoe, 2004; Birke et al., 1995) has been hypothesized to result in reduced first metatarsal motion during gait in individuals with DM (Glasoe et al., 1999) thus predisposing to the development of foot ulcers.

While the first ray is an important component of the twisted plate model of the foot, first ray mechanics in gait are still controversial. Current studies suggest that the first metatarsal is plantarflexed during early stance and continues to dorsiflex about 10° relative to the hindfoot until 70% of stance (Cornwall and McPoil, 2002; Cornwall and McPoil, 1999; MacWilliams et al., 2003; Wearing, 1998). However, recent evidence demonstrates minimal lowering of the proximal first metatarsal during stance (Wilken et al., 2005) and suggesting that the excursion between the first metatarsal and calcaneus comes predominantly from calcaneal motion.

Evidence substantiating altered foot function as it relates to segmental foot mobility during gait in individuals with DM is limited. The few studies that have used multi-segment kinematic models (MacWilliams et al., 2003; Allen, 2004; Nawoczenski et al., 1999; Leardini, 1999) have been conducted on non-DM subjects with intact sensation. Their extrapolation to subjects with DM, who have impairments such as loss of protective sensation and increased connective tissue stiffness, may not be valid.

Thus, while intrinsic foot mobility has been identified as an important potential contributor to foot function, especially in individuals with DM, the role of limited foot mobility in gait remains poorly understood. The purpose of our study was to examine segmental foot mobility during gait in subjects with and without DM and neuropathy. These results are important because they may help uncover mechanisms underlying altered segmental foot function in individuals with DM. Altered foot kinematics may also contribute to the development of high loads on the plantar aspect of the foot and thus potential tissue breakdown. An enhanced understanding of foot function in patients with DM may help the development of patient specific foot risk surveillance and suggest strategies for individualized footwear intervention.

## 2. Methods

### 2.1. Subjects

All procedures were approved by the Institutional Review Board at the University of Iowa Hospitals and Clinics. Subjects with DM and neuropathy ($n = 15$) comprised the study group; non-diabetic subjects ($n = 15$) comprised the control (Ctrl) group. Subjects with DM were included based on the diagnosis of DM (ADA criteria (Diagnosis and Classification of Diabetes Mellitus, 2006)) and excluded if they had: current foot ulcer, great toe or transmetatarsal amputation, ipsilateral or contralateral Charcot neuroarthropathy or clinical symptoms of other musculoskeletal lower limb pathology. Presence of neuropathy was documented using 5.07 Semmes–Weinstein monofilaments (Mueller, 1996) and vibration perception threshold (VPT) of 25 V or higher (Pham, 2000). Subjects in the control group were screened for diabetes and matched in age and gender to subjects with DM. Subject characteristics are summarized in Table 1.

### 2.2. Data acquisition

Kinematic and kinetic data were acquired as subjects walked along a 10 m walkway at 0.89 m/s (2 mph). An overhead timing chain was used to obtain/monitor walking speed. Kinematic data were collected at 120 Hz using an active marker system (Optotrak, NDI, Waterloo, Canada). Three infrared markers were placed in a non-collinear arrangement to define technical co-ordinate systems for each of the following segments: first metatarsal, forefoot, calcaneus and leg. Kinetic data were collected at 360 Hz using a forceplate embedded in the walkway (Kistler Inc., Amherst, NY, USA).

Kinematic and kinetic data were low-pass filtered using a fourth order butterworth filter with cut-off frequencies of 6 and 8 Hz, respectively and processed using Visual3D software (C-motion Inc., Rockville, MD, USA). A threshold of 10 N was used to determine heelstrike and toe off from the force plate data. Kinematic marker data were used to confirm that subjects were able to achieve and maintain walking speed and to calculate stride length. A minimum of five successful trials were collected for each subject. A trial was considered successful if the subject made clean forceplate contact on the tested side without targeting.

### 2.3. Multisegment kinematic model of the foot

A multi-segment kinematic model of the foot based on (Wilken et al., 2004) was used to examine segmental mobility of the foot. This model has been validated by Wilken

Table 1
Demographic data from study and control groups, expressed as mean (SD)

| | DM | Control |
|---|---|---|
| N | 15 | 15 |
| Age (yrs) | 58 (11) | 56 (12) |
| Gender F:M | 5:10 | 5:10 |
| Height (m) | 1.77 (0.11) | 1.75 (0.10) |
| Mass (kg) | 90.6 (13.8) | 74.6 (13.3) |
| VPT (V) | 48 (5) | 13 (6) |
| HbA1c% | 8.1 (1.1) | |
| Type 2 | 12 i.e. 80% | |
| Duration (yrs) | 19 (6) | |

et al. (2004) and has several strengths. It is anatomically based and lends itself to the creation of subject-specific kinematic models. The foot was segmented into the first metatarsal, calcaneus and forefoot, where first metatarsal and calcaneus segments referred to the underlying bony anatomy while the forefoot segment comprised metatarsals 2–5. This definition of the forefoot segment, consistent with previous kinematic models (Carson, 2001; Hunt, 2001) was used to facilitate comparison of results across studies. Motion of the calcaneus relative to the tibia encompasses the talocalcaneal (subtalar) as well as the talocrural (ankle) joints. Results obtained from in vivo cadaver models suggest that the majority of dorsiflexion–plantarflexion motion between the calcaneus and tibia may be attributed to the ankle-joint, while abduction–adduction and inversion–eversion may be attributed to subtalar joint. (Scott and Winter, 1991; Piazza, 2005) Since the first metatarsal and calcaneus are key elements in the medial longitudinal arch, (Cavanagh, 1997; Saltzman et al., 1995) motion between the first metatarsal and calcaneus is considered representative of motion of the arch. (Wearing, 1998; Wilken, 2006; Tome, 2006) The segments defined in this model have well-grounded conceptual meaning (Sarrafian, 1987), as well as targeted the segments of interest. Anatomical landmarks were identified as virtual points with respect to the relevant technical co-ordinate system. Anatomically based local coordinate systems were established using the criteria defined in Tables 2 and 3.

Motion of the distal segment was expressed relative to the proximal segment (Woltring, 1991) and was calculated using Euler angles with the following sequence of rotations: sagittal, frontal and transverse. Motion of each segment relative to the lab global co-ordinate system (GCS) was also examined. While the former convention has widespread clinical relevance, the latter allows us to examine the contribution of each moving segment to relative motion between the two. Processed kinematic data were time normalized to 100 percent stance. Stance phase mean was subtracted from pattern to correct for systematic offsets (Hunt, 2001). The application of this correction eliminates systematic offsets between groups and helps reduce between-subject variability, allowing for comparisons of range, timing and pattern of motion between the study and control groups.

### 2.4. Statistical analysis

A two-sample *t*-test was used to assess differences between the two groups ($\alpha = 0.05$). To control Type 1 error rate when performing multiple pair-wise comparisons, an

Table 2
Definition of Local Co-ordinate Systems (Wilken et al., 2004)

| Segment | Axis | Definition |
|---|---|---|
| First metatarsal | $X$ | Aligned with long axis of first metatarsal |
| | $Y$ | Orthogonal to $X$ and $Z$ axes |
| | $Z$ | Parallel to floor and orthogonal to $X$ axis |
| Lateral forefoot | $X$ | Aligned with long axis of second metatarsal |
| | $Y$ | Orthogonal to $X$ and $Z$ axes |
| | $Z$ | Orthogonal to long axis of second metatarsal and parallel to the floor |
| Calcaneus | $X$ | Posterior heel to midpoint of foot at the level of the fifth metatarsal flair |
| | $Y$ | Calcaneal bisector |
| | $Z$ | Orthogonal to $X$ and $Y$ axes |
| Leg | $X$ | Orthogonal to $Y$ and $Z$ axes |
| | $Y$ | Passing through midpoint of femoral condyles and malleoli |
| | $Z$ | Aligned with malleoli and passing through mid malleolar point (orthogonal to $Y$) |

Table 3
Marker placement (Wilken et al., 2004)

| Segment | Marker | Location |
|---|---|---|
| First metatarsal | 1 | Mounted on triad on dorsal medial surface of first metatarsal |
| | 2 | Mounted on triad on dorsal medial surface of first metatarsal |
| | 3 | Mounted on triad on dorsal medial surface of first metatarsal |
| Lateral forefoot | 4 | Proximal end of second metatarsal |
| | 5 | Distal end of second metatarsal |
| | 6 | Distal end of fifth metatarsal |
| Calcaneus | 7 | Posterior surface of calcaneus |
| | 8 | Lateral aspect of calcaneus superior to calcaneal fat pad |
| | 9 | Lateral aspect of calcaneus superior to calcaneal fat pad |
| Leg | 10 | Medial surface of tibia |
| | 11 | Medial surface of tibia |
| | 12 | Medial surface of tibia |

adjusted *P*-value ($\alpha = 0.05$ per segment) was used to determine statistical significance based on the number of comparisons made.

## 3. Results

Subjects in both groups walked with similar speed (0.89 (SD, 0.13) and 0.93 (SD, 0.11) m/s, DM and Ctrl, respectively, $P = 0.169$) and stride length (1.08 (SD, 0.15) and 1.12 (SD, 0.10) m, DM and Ctrl, respectively, $P = 0.166$). Because of the differences in BMI the relationships between BMI and kinematic variables were assessed and determined to be not a confounding factor ($r^2 < 12\%$).

### 3.1. Segmental kinematics expressed relative to proximal segment

Subjects with DM showed reduced frontal plane excursion of the calcaneus relative to the tibia, accompanied by reduced eversion (Fig. 1h and Table 4). Subjects with DM also showed reduced sagittal plane excursion (Fig. 1g) of the calcaneus relative to the tibia. Decreased excursion of the first metatarsal relative to the calcaneus in the frontal plane (Fig. 1b and Table 4), as well as transverse plane (Fig. 1c), was noted in subjects with DM. Trends towards reduced frontal plane excursion of the forefoot relative to the calcaneus were noted in subjects with DM (Fig. 1e).

### 3.2. Segmental kinematics expressed relative to the lab

Reduced sagittal plane calcaneal excursion and trends towards reduced frontal plane calcaneal excursion and eversion (Fig. 2h and Table 5) were noted in subjects with DM. The first metatarsal as well as forefoot showed less sagittal plane excursion (Fig. 2a, d, and Table 5) in subjects with DM. In addition, the forefoot showed decreased frontal plane excursion in subjects with DM (Fig. 2e), similar trends were noted in the transverse plane (Fig. 2f). Sagittal plane excursion of the tibia was reduced in subjects with DM (Fig. 3a and Table 5).

## 4. Discussion

We applied a multi-segment kinematic model to examine foot function in individuals with DM and neuropathy compared to non-diabetic control subjects. Our results

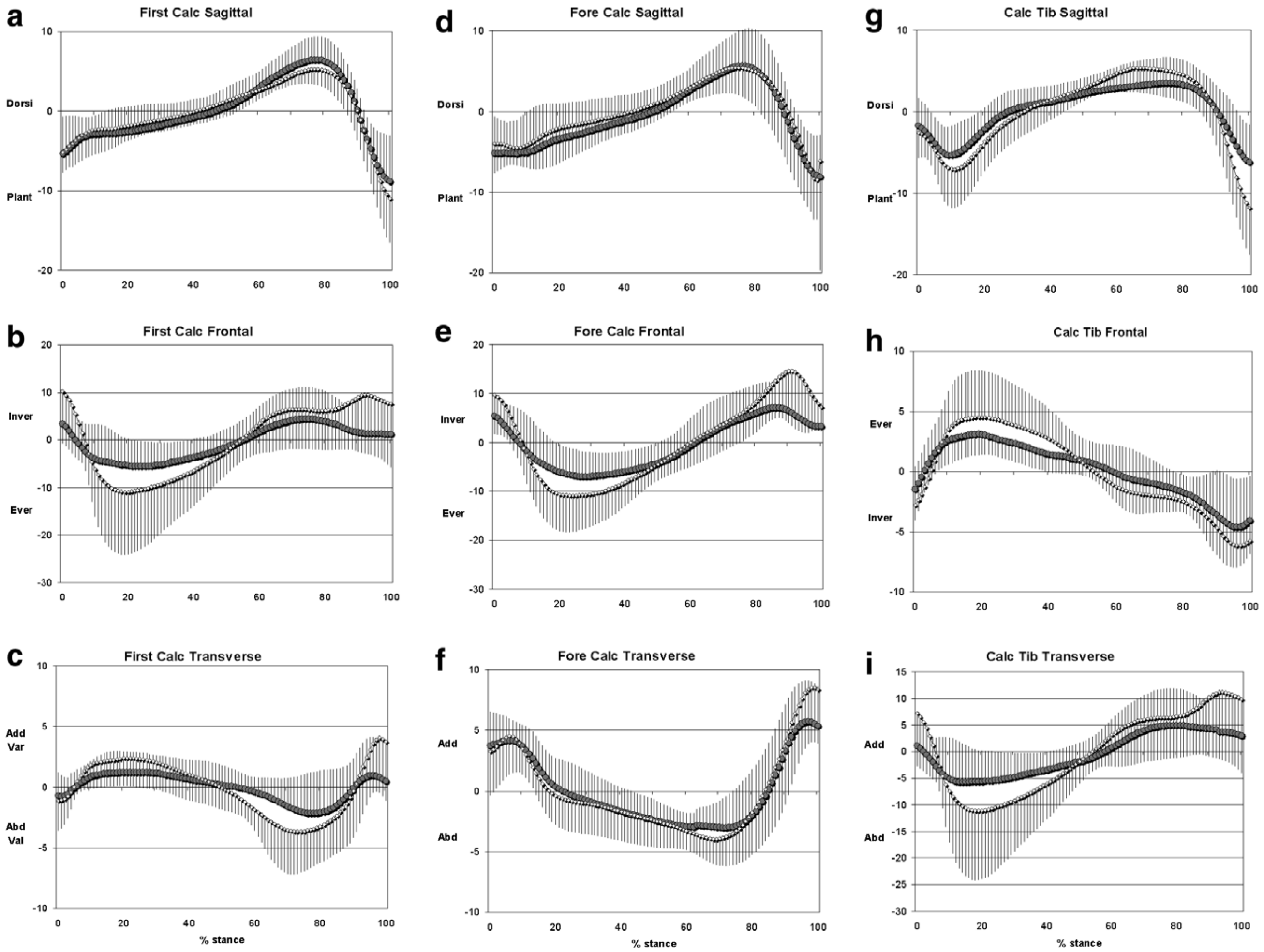

Fig. 1. Ensemble averaged kinematics of the first metatarsal, forefoot and calcaneus relative to the proximal segment. Circles represent subjects with DM, diamonds represent Ctrl subjects; error bars represent 1SD.

Table 4
Summary of segmental kinematics, mean (SD), expressed relative to the proximal segment

| Segment | Plane | Parameter | DM | Ctrl | *P* value |
|---|---|---|---|---|---|
| First metatarsal | Sagittal | Dorsi | 6.5 (3.8) | 5.6 (1.9) | 0.147 |
| | | Range | 13.0 (2.5) | 14.7 (3.3) | 0.270 |
| Forefoot | Sagittal | Dorsi | 6.4 (2.6) | 5.9 (2.5) | 0.302 |
| | | Range | 13.8 (3.3) | 15.3(4.0) | 0.139 |
| Calcaneus | Sagittal | Dorsi | 5.9 (2.1) | 6.7(2.2) | 0.015 |
| | | Range | 12.7 (4.3) | 19.6 (4.4) | <0.001 |
| | Frontal | Ever | 4.5 (2.0) | 6.5 (2.4) | 0.010 |
| | | Range | 9.5 (4.3) | 15.0 (3.9) | <0.001 |

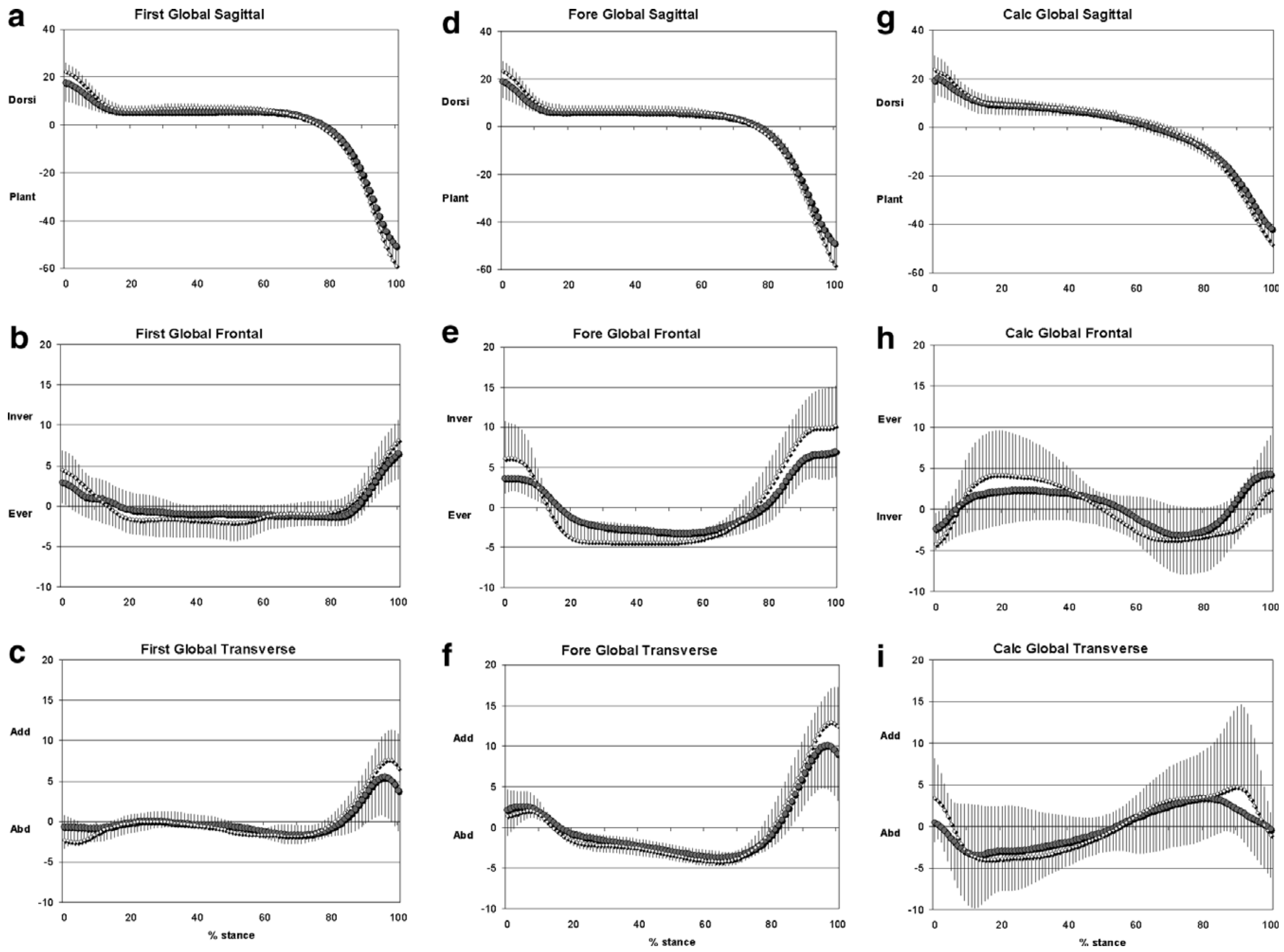

Fig. 2. Ensemble averaged kinematics of the first metatarsal, forefoot and calcaneus relative to the GCS. Circles represent subjects with DM; diamonds represent Ctrl subjects; error bars represent 1SD.

revealed significant differences in patterns of segmental mobility between the two groups, with DM subjects showing lower magnitudes of motion. The reductions in motion were not generalized – they were particularly dramatic in the calcaneus compared to the forefoot and first metatarsal. Our results underscore the complexity of segmental foot function during gait; motion at one joint has important consequences on motion at neighboring joints. Our findings provide new insights on the nature of impairments in segmental foot function in individuals with DM.

During gait, foot-floor interaction begins with heel contact which places significant demands on the subtalar joint in terms of mobility and shock absorption (Saltzman and Nawoczenski, 1995). In agreement with reports based on surface markers (MacWilliams et al., 2003; Allen, 2004; Leardini, 1999; Hunt, 2001; Levangie and Norkin, 2001; Neumann, 2002; Hunt et al., 2000) as well as bone pins (Westblad, 2002), our results showed that the calcaneus undergoes rapid pronation in early stance. In order to examine the contribution of each moving segment to rela-

Table 5
Summary of segmental kinematics, mean (SD), expressed relative to the GCS

| Segment | Plane | Parameter | DM | Ctrl | *P* value |
|---|---|---|---|---|---|
| First Ray | Sagittal | Dorsi | 18.3 (6.7) | 22.2 (3.8) | 0.032 |
| | | Range | 68.8 (12.5) | 81.1 (8.8) | 0.002 |
| Forefoot | Sagittal | Dorsi | 19.3 (6.6) | 23.3 (4.3) | 0.032 |
| | | Range | 68.4 (12.4) | 81.4 (8.7) | 0.001 |
| Calcaneus | Sagittal | Dorsi | 22.3 (5.7) | 24.9 (4.1) | 0.077 |
| | | Range | 64.1 (10.4) | 72.8 (7.2) | 0.006 |
| | Frontal | Ever | 3.1 (3.0) | 5.2 (3.5) | 0.037 |
| | | Range | 9.7 (7.5) | 12.6 (4.6) | 0.021 |
| Tibia | Sagittal | Range | 60.0 (7.2) | 66.3 (4.6) | 0.003 |
| | Frontal | Range | 5.9 (1.9) | 5.0 (1.5) | 0.145 |

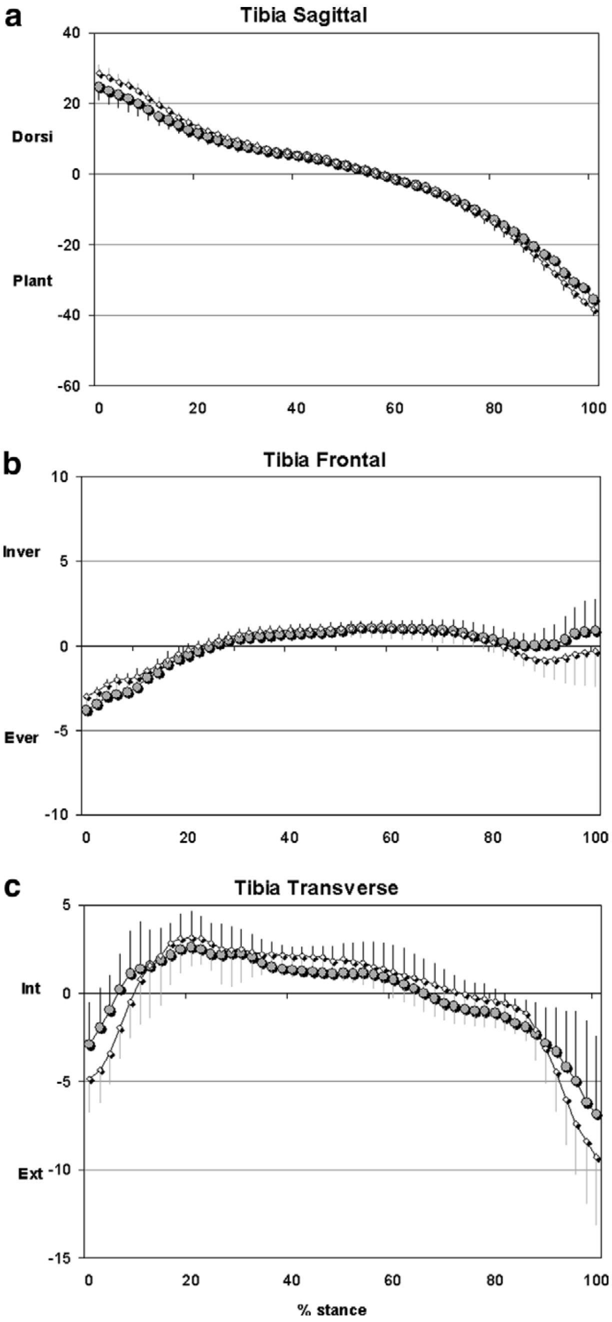

Fig. 3. Ensemble averaged kinematics of the tibia relative to the GCS. Circles represent subjects with DM; diamonds represent Ctrl subjects; error bars represent 1SD.

tive motion between the two segments, joint kinematics were expressed in two different ways. First, motion of the distal segment relative to the next proximal segment was examined because it has direct clinical relevance. Next, segmental kinematics were expressed relative to the global coordinate system to examine motion of each segment. Our results revealed minimal differences in tibial kinematics (Fig. 3), highlighting changes in intrinsic foot function during gait in individuals with DM. Calcaneal pronation, manifest as calcaneal eversion (Figs. 1h and 2h) and abduction (Figs. 1i and 2i), was accompanied by first metatarsal (Figs. 1b and 2b) and forefoot eversion in early stance (Figs. 1e and 2e), supporting the argument that the foot is flexible and ‘splays’ during this interval. In subjects with DM, we found a reduction in the magnitude of peak calcaneal eversion and trends towards reduced abduction (Fig. 1h and i, and Table 4).

The reduction in calcaneal motion is important because subtalar pronation has important consequences on joints proximal, as well as distal to it. Subtalar motion reduces rotational stresses that would otherwise be transferred proximally (Perry, 1983). Lack of eversion at the subtalar joint may be expected to render the axes of the transverse tarsal joints out of alignment thus decreasing the amount of motion possible though the midfoot for shock absorption (Elftman, 1969; Blackwood, 2005). This phenomenon may help explain the reduced forefoot eversion (Figs. 1e and 2e) noted in subjects with DM.

Loss of frontal plane mobility of the calcaneus may be attributed to several discrete yet coexisting processes in subjects with DM. While it is unlikely that subjects in either group approximated end range-of-motion of the subtalar joint (Duffin, 1999; Mueller, 1989), increased stiffness of the subtalar joint as well as reduced compliance of the calcaneal heel pad (Kao et al., 1999) may contribute to reduced excursion. The reduction of joint excursion may also be ascribed to neuropathy. Previous studies (Nurse and Nigg, 2001; Giacomozzi, 2002) have suggested that the absence of cutaneous feedback results in the adoption of a more conservative walking strategy. Reductions in forefoot motion may be due to lack of eversion of the subtalar joint but could also be due to factors intrinsic to the transverse tarsal joint, such as stiffness of talonavicular and calcaneocuboid joints. In subjects with DM, non-enzymatic glycosylation of collagen may contribute to increased stiffness of the distal joints of the feet, hindering the ability of the foot to deform and transition from a rigid lever to a more flexible configuration.

Calcaneal motion, through its effect on the talonavicular joint may influence arch mobility. Gradual arch deformation, discerned as sagittal plane motion of the first metatarsal relative to the calcaneus (Fig. 1a) followed calcaneal pronation in both groups, in agreement with previous reports (MacWilliams et al., 2003; Leardini, 1999; Carson, 2001; Hunt, 2001). In terminal stance, calcaneal plantarflexion, under the influence of the gastrocnemius-soleus complex, resulted in rapid tensing of the arch, providing midfoot stability. Particularly striking in both groups, was that medial longitudinal arch deformation was accompanied by nearly static first metatarsal inclination (Fig. 2a) supporting the theory that calcaneal mobility is a major contributor to arch motion while the first metatarsal provides distal stability. These data support the contention that the talus and calcaneus move over the relatively fixed naviculo-cuboid unit (Levangie and Norkin, 2001; Wilken, 2006).

Early calcaneal pronation was followed by gradual supination in both groups. These findings agree with the traditional understanding of foot mechanics wherein swing phase of the contralateral limb facilitates external rotation of the stance limb, which in turn helps initiate subtalar supination (Neumann, 2002; Inman, 1993). Traditional foot models predict that forefoot pronation will accompany calcaneal supination in order for the sole of the foot to maintain contact with the ground. Consistent with this theory, our results showed that calcaneal supination was accompanied by the first metatarsal and forefoot staying static in eversion and abduction.

At terminal stance, in agreement with previous reports (Cornwall and McPoil, 2002; Leardini, 1999; Carson, 2001; Hunt, 2001; Arndt, 2004), calcaneal supination was accompanied by first metatarsal and forefoot supination to convert the foot into a rigid lever. In subjects with DM, decreases in calcaneal plantarflexion (Figs. 1g and 2g), first metatarsal and forefoot supination were noted (Figs. 1 and 2e, h). Decreased calcaneal plantarflexion may result from reduced plantarflexor contraction at push off (Maluf, 2004). Decreases in first metatarsal and forefoot motion accentuate the finding that it takes less supination in the foot with DM to create a stable, rigid lever at push off. In subjects with DM, a greater proportion of midfoot stability may be derived from modified/stiffer soft tissue such as the plantar fascia (Giacomozzi, 2005).

In summary, we applied a multisegment kinematic foot model with established reliability and validity to examine segmental foot mobility in individuals with and without DM and neuropathy. Our findings agree with the traditional understanding of foot mechanics and shed new light on patterns and magnitude of motion during gait. Decreases in frontal plane calcaneal motion were accompanied by reduced midfoot mobility, discerned as reduced first metatarsal and forefoot motion. Our findings indicate that there are dramatic differences in foot function in early stance in shock absorption and in propulsion in terminal stance.

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