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Comparison of *in vivo* segmental foot motion during walking and step descent in patients with midfoot arthritis and matched asymptomatic control subjects

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ABSTRACT

The purpose of this study was to compare *in vivo* segmental foot motion during walking and step descent in patients with midfoot arthritis and asymptomatic control subjects. Segmental foot motion during walking and step descent was assessed using a multi-segment foot model in 30 patients with midfoot arthritis and 20 age, gender and BMI matched controls. Peak and total range of motion (ROM), referenced to subtalar neutral, were examined for each of the following dependent variables: 1st metatarso-phalangeal (MTP1) dorsiflexion, 1st metatarsal (MT1) plantarflexion, ankle dorsiflexion, calcaneal eversion and forefoot abduction. The results showed that, compared to level walking, step descent required greater MTP1 dorsiflexion ($p<0.01$), MPT1 plantarflexion ($p<0.01$), ankle dorsiflexion ($p<0.01$), calcaneus eversion ($p=0.03$) and forefoot abduction ($p=0.01$), in all subjects. In addition, step descent also necessitated greater MTP1 dorsiflexion ($p<0.01$), ankle dorsiflexion ($p<0.01$) and forefoot abduction ($p=0.02$) excursion compared to walking. Patients with midfoot arthritis responded differently to the step task compared to control subjects in terms of MT1 and calcaneus eversion excursion. During walking, patients with midfoot arthritis showed significantly less MT1 plantarflexion excursion compared to control subjects ($p=0.03$). However, during step descent, both groups showed similar MT1 plantarflexion excursion. During walking, patients with midfoot arthritis showed similar calcaneus eversion excursion compared to control subjects. However, during step descent, patients with midfoot arthritis showed significantly greater calcaneus eversion excursion compared to control subjects ($p=0.03$). Independently or in combination, these motions may contribute to articular stress and consequently to symptoms in patients with midfoot arthritis.

1. Introduction

Patients with midfoot arthritis present with persistent midfoot pain that limits weight bearing and physical activity (Teng et al., 2002). The etiology of midfoot arthritis includes primary, inflammatory and post-traumatic causes; post-traumatic arthritis is the most common (Hardcastle et al., 1982). Previous reports have estimated that the incidence of midfoot injuries is 55,000 per year (Hardcastle et al., 1982). More recently, a retrospective review of restrained front seat occupants noted that the relative incidence of foot and ankle injuries, particularly midfoot disruptions, has increased (Richter et al., 2001). Due to the multiple articulations that comprise the midfoot, even minimal disruption of the tarsometatarsal complex is indicative of significant injury (Myerson et al., 1986). In addition, as our population ages, the long-term effects of chronic increased loads sustained with high-heeled footwear may also contribute to the development of degenerative midfoot arthritis (Yu et al., 2007). Irrespective of the etiology, midfoot arthritis has been reported to be the inevitable sequelae of tarsometatarsal disease (Arntz and Hansen, 1987).

The high prevalence of pain in patients with midfoot arthritis has been linked to purported loss of midfoot stability and consequent abnormal patterns of foot motion during functional activities (Teng et al., 2002). In particular, patients report stair descent as being particularly painful. Stair descent is acknowledged to be a more challenging functional activity compared to walking because of the greater magnitudes of motion as well as loading sustained during stair descent (Andriacchi et al., 1980; Costigan et al., 2002). Evidence in support of the contention that stair descent is considerably more demanding than walking comes from studies demonstrating increased sagittal plane

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motion at the hip, knee and ankle joints during stair descent compared to level walking in healthy subjects (Andriacchi et al., 1980). The increase in motion has been accompanied by increased net joint moments (Andriacchi et al., 1980) and consequent increases in joint contact forces (Costigan et al., 2002) during stair descent compared to walking. However, investigations examining the effect of stair descent on segmental foot motion are lacking.

Multi-segment foot models have been used to successfully identify differences in foot function in patients with foot pathology compared to control subjects. Compared with healthy control subjects, patients with rheumatoid arthritis showed excessive subtalar eversion (Woodburn et al., 2003; Turner et al., 2008) and reduced forefoot range of motion (Khazzam et al., 2007). In patients with posterior tibial tendon dysfunction, increased calcaneal eversion and forefoot abduction was found compared to a matched controls (Tome et al., 2006). Patients with hallux rigidus demonstrated reduced hallux dorsiflexion as well as reduced metatarsal plantarflexion compared to control subjects (Canseco et al., 2008; Nawoczenski et al., 2008). In patients with diabetes, reductions in calcaneal eversion and forefoot abduction have been noted (Rao et al., 2007). These recent reports support the contention that impairments in foot function during walking can be effectively delineated in patients with foot pathology. However, these previous studies assessed foot function during level walking and not in more demanding functional activities that provoke patients' symptoms.

Recent reports have examined foot function in tasks other than straight-ahead walking, such as walking on an incline (Huang et al., 2006). The latter tasks are more challenging than level walking and therefore, may be more effective in unmasking underlying impairments in foot function. However these data are absent in patients with midfoot arthritis. Further no studies have examined foot function during stair descent. In order to design the most effective intervention and minimize the secondary loss of function associated with pain, potentially detrimental changes in segmental foot motion during functional activities that exacerbate symptoms must be identified. Based on these data, corrective intervention may be designed and instituted to optimize functional outcomes. The purpose of this study is to compare *in vivo* segmental foot motion during walking and step descent tasks in patients with midfoot arthritis and asymptomatic matched control subjects. Based on previous studies in patients with rheumatoid arthritis (Woodburn et al., 1999; Turner et al., 2008), and ankle arthritis (Huang et al., 2006; Khazzam et al., 2006), we expect to see increased calcaneal eversion and forefoot abduction, and decreased segmental foot ROM in patients with midfoot arthritis compared to control subjects. Based on recent reports highlighting the importance of ambulatory mechanics in the evolution of knee osteoarthritis (Andriacchi and Mundermann, 2006) and the increased demands associated with step descent, we hypothesize that patients with midfoot arthritis will show increased peak motion as well as ROM during the step task compared to walking.

2. Methods

2.1. Subjects

50 subjects participated in this study, 30 with midfoot arthritis and 20 control subjects, matched in age, gender and BMI. All procedures were approved by the review boards of the University of Rochester and Ithaca College; informed consent was sought prior to initiating study procedures.

2.2. Inclusion criteria

All patients sought care at the University of Rochester Medical Center, USA. All patients presented with unilateral symptoms, comprising pain on the dorsum of the foot, localized to the tarsometatarsal region and aggravated by weight bearing. The diagnosis of isolated midfoot arthritis was confirmed by radiographic evidence of degenerative changes at one or more tarsometatarsal joints on antero-posterior and lateral weight-bearing X-rays. All patients with midfoot arthritis were invited to participate in this study with the following exclusion criteria: (1) concomitant injury or previous surgery of the lower extremity, (2) conditions such as stroke, inflammatory arthritis, diabetes, or (3) use an assistive device. A single Fellowship-trained foot and ankle orthopedic surgeon (JB) screened all subjects. None of the patients recollected a traumatic event preceding their symptoms. Control subjects were recruited from the community using fliers, screened by a single trained physical therapist (SR) for lower extremity pain and/or dysfunction and were matched for age, gender and BMI to patients with midfoot arthritis (Table 1).

2.3. Data acquisition

All data were collected at the Movement Analysis Lab at the Department of Physical Therapy, Ithaca College–Rochester Center, Rochester, NY, USA.

2.3.1. Patients' self-reported foot function

The foot function index-revised (FFI-R), a region-specific health-related quality-of-life instrument was used to assess patients' foot function. The FFI-R consists of 34 questions organized into the following subscales: pain, stiffness, disability, activity limitation and psychosocial issues. The reliability and validity of the foot function index has been established in patients with chronic foot disorders (Budiman-Mak et al., 1991; SooHoo et al., 2006). In 2006, the foot function index was revised to include a more rigorous theoretical model. The construct validity and reliability of FFI-R was established in field testing on a sample of 92 patients,

Table 1
Summary of demographic characteristics, expressed in mean (SD).

Variable	Midfoot arthritis	Control
Age (years)	62 (7) range: 47–78	58 (8) range: 48–78
BMI (kg/m^2)	30 (6) range: 20–46	29 (5) range: 22–41
M:F	2:28	1:19
Radiographic measures of foot architecture, compared to normative data from the literature		
Calcaneal inclination	17 (5) range: 9–30	22 (6)[a]
Calcaneal 1st metatarsal angle	145 (9) range: 163–129	132 (10)[b]
Radiographic measures of arthritis severity, using Kellegren Lawrence grades[c]		
1st and 2nd Tarso-metatarsal joints	2.3 range: 0–4	
Naviculo-cuneiform joint	1.2 range: 0–2	
Talo-navicular joint	0.40 range: 0–1	
Calcaneo-cuboid joint	0	
Subtalar joint	0.20 range: 0–1	

[a] Data from Cavanagh et al. (1997).

[b] Data from Saltzman et al. (1995).

[c] Rating scale based on Greisberg et al. (2003) and Menz et al. (2007), higher scores indicate greater radiographic severity. Range values have been obtained from the current study cohort.

of whom, over two-thirds (69%) had degenerative arthritis of the foot (Budiman-Makb et al., 2006). For these reasons, the FFI-R was selected to assess patients with midfoot arthritis in the present investigation.

2.3.2. *In vivo segmental foot motion*

A 5-segment kinematic foot model with previously established validity (Umberger et al., 1999; Tome et al., 2006) was used to examine *in vivo* segmental foot motion. A magnetic tracking system (Flock of Birds, Burlington, VT) was used to acquire kinematic data at 98 Hz. Position and orientation of the six-degree-of-freedom sensors (18 mm × 8 mm × 8 mm) was obtained with nominal static positional accuracy of 1.8 mm RMS and static angular accuracy of 0.5° RMS (AscensionTechnologyCorporation, 2000). Sensors were placed on the subject's skin over the hallux, 1st and 2nd metatarsal, calcaneus and tibia and secured with double-sided tape. Wires were secured using pre-wrap and maintained out of the subject's path by study personnel (SR) during the testing session. Local co-ordinate systems were established by digitizing anatomical landmarks. All kinematic data were collected in the barefoot condition. Additional details related to the kinematic foot model are presented in Fig. 1, Appendix A and in an Online Supplement.

For walking trials, data were collected as patients walked along a 5 m walkway at self-selected walking speed, monitored to within ±5% using an infra-red timing device (Brower Systems Inc, UT). Walking speed did not differ between the two groups (0.69 ± 0.20 and 0.74 ± 0.17 m/s, patients with midfoot arthritis and matched control subjects, respectively, $p = 0.36$). To simulate stair descent, patients stepped off a standard step height (19.7 cm) to the floor. (InternationalCodeCouncil, 2009) Based on patients' symptoms, stair descent was expected to be challenging for patients with midfoot arthritis. However, we did not want data acquisition procedures to stress patients' feet to the point of causing injury. For these reasons, patients were instructed to perform unilateral step descent. All patients were able to complete the step descent task without acute worsening of symptoms. Consistent with definitions used in previous reports (Costigan et al., 2002), the stance phase of stair descent was identified using initial contact and toe off of the stance limb.

Kinematic data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency of 6 Hz and analyzed using MotionMonitor^{TM} software (Innovative Sport Training, Chicago, IL). Euler angles, representing three sequential rotations (Z–X–Y) were used to describe joint motion. Dependent variables of interest (Fig. 2) included: calcaneal eversion, forefoot abduction, 1st metatarsal

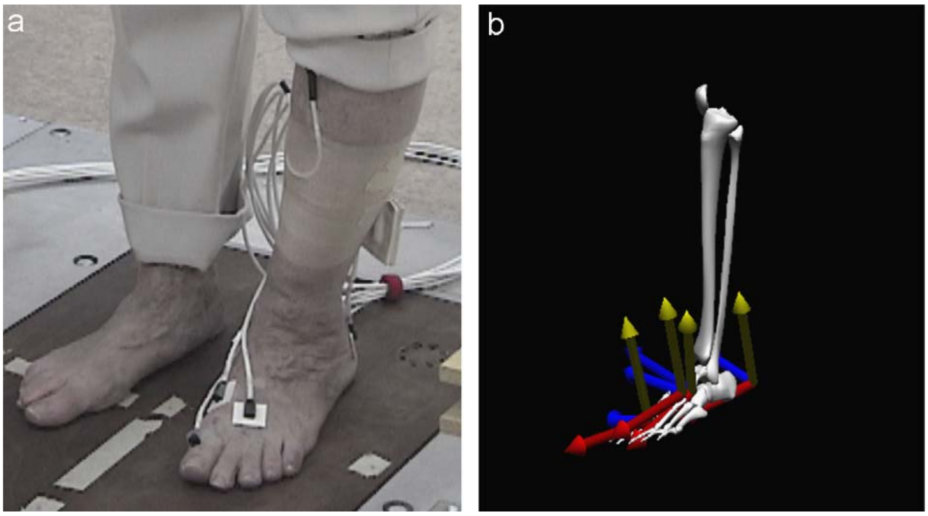

Fig. 1. *In vivo* kinematic foot model used to track segmental foot motion and subject-specific anatomical co-ordinate system.

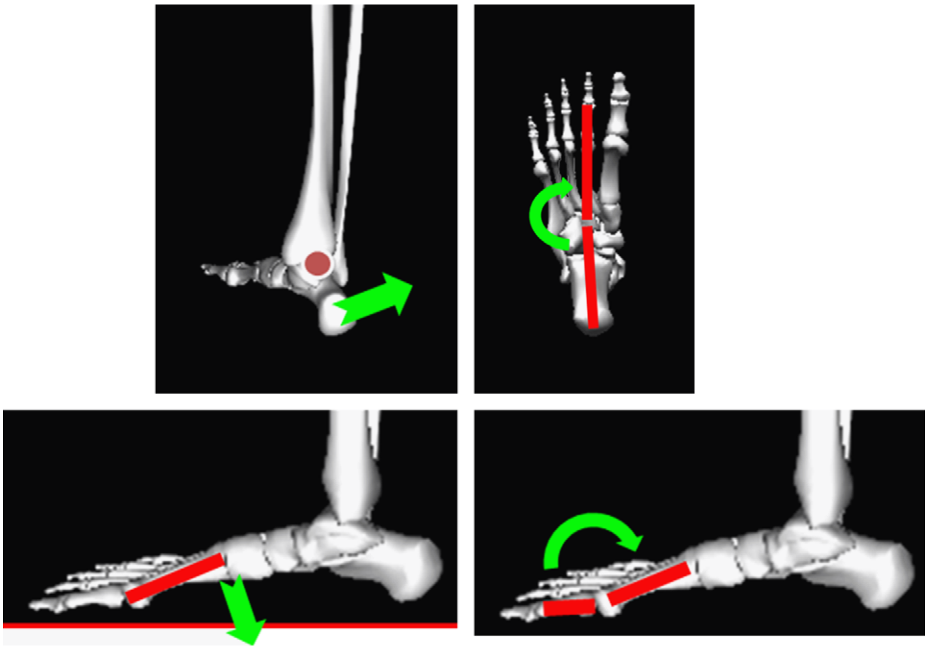

Fig. 2. Graphic depiction of kinematic-dependent variables. (top left) calcaneal eversion: motion of the calcaneus relative to tibia about an antero-posterior axis (top right) forefoot abduction: motion of the 2nd metatarsal relative to calcaneus, about a supero-inferior axis), (bottom left) 1st metatarsal plantarflexion: motion of the 1st metatarsal relative to the lab (global) co-ordinate system, about a medio-lateral axis (bottom right) 1st metatarso-phalangeal (MTP) dorsiflexion: motion of the hallux relative to 1st metatarsal about a medio-lateral axis.

(MT1) plantarflexion and 1st metatarso-phalangeal joint (MTP1) dorsiflexion. Peak values for all dependent variables were referenced to subtalar neutral (Houck et al., 2008). A single tester (SR) determined subtalar neutral for all subjects, while they stood in bilateral weight bearing stance. The methods for referencing kinematic data are consistent with those reported in recent studies (Woodburn et al., 2003; Houck et al., 2008). In addition to peak motion, total peak-to-peak range of motion (ROM) was also assessed for each variable.

2.4. Statistical analysis

Data were assessed for normality and variance homogeneity. FFI-R scores between groups were compared using a two-sample *t*-test. A 2-way ANOVA was to examine the effect of Group (between-subjects effect) and Activity (within-subjects effect) on all dependent variables related to *in vivo* segmental foot motion. Interaction effects were examined first (Group × Activity). If an interaction effect was not present, data from both Groups were combined and the effect of Activity was examined. If an interaction effect was present, data were sorted by Group and effect of Activity was assessed within each Group. Bonferroni-adjusted comparisons were used to assess the statistical significance of pair-wise comparisons.

3. Results

3.1. Functional outcomes

Patients with midfoot arthritis reported significantly higher FFI-R scores compared to matched control subjects. An examination of subscale scores revealed that patients with midfoot arthritis also scored significantly higher on all the subscales (pain, activity limitation, disability and psychosocial issues) of the FFI-R compared to matched control subjects ($p<0.01$ for all subscales as well as total score, Table 2).

3.2.. In vivo segmental motion

3.2.1. Peak motion

No evidence was found for a Group × Activity interaction for any of the following dependent variables (MTP1 dorsiflexion, $p=0.25$; MT1 plantarflexion, $p=0.63$, ankle dorsiflexion, $p=0.29$; calcaneal eversion, $p=$ 0.23; forefoot abduction, $p=0.96$) All subjects demonstrated significantly greater peak MTP1dorsiflexion ($p<0.01$), MT1 plantarflexion ($p<0.01$), ankle dorsiflexion ($p<0.01$), calcaneal eversion ($p=0.03$) and forefoot abduction ($p=0.01$) during step descent compared to walking (Fig. 3).

3.2.2. Total ROM

No evidence was found for a Group × Activity interaction for any of the following dependent variables (ankle dorsiflexion, $p=0.61$; forefoot abduction, $p=0.33$; and MTP1dorsiflexion, $p=0.65$). All subjects demonstrated significantly greater total range of ankle dorsiflexion ($p<0.01$), forefoot abduction ($p=0.02$) and MTP1dorsiflexion ($p<0.01$), during step descent compared to walking (Fig. 4).

A significant Group × Activity Interaction effect was found for both, 1st metatarsal plantarflexion ROM ($p=0.02$) and calcaneal eversion ROM ($p=0.01$). During walking, patients with midfoot arthritis showed significantly less MT1 plantarflexion range of motion compared to control subjects($p=0.03$). However, in the step task, both groups showed similar MT1 plantarflexion range of motion (Fig. 5a). During walking, patients with midfoot arthritis

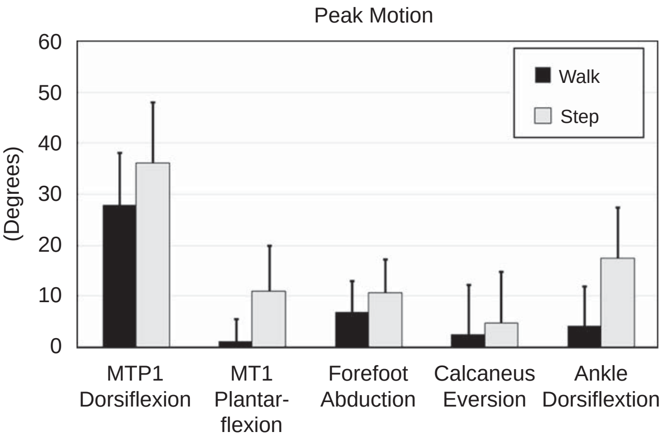

Fig. 3. All subjects demonstrated significantly more peak MTP1 dorsiflexion ($p<0.01$), MT1 plantarflexion ($p<0.01$), ankle dorsiflexion ($p<0.01$), calcaneal eversion ($p=0.03$) and forefoot abduction ($p=0.01$) during step descent compared to walking. Error bars indicate standard deviation.

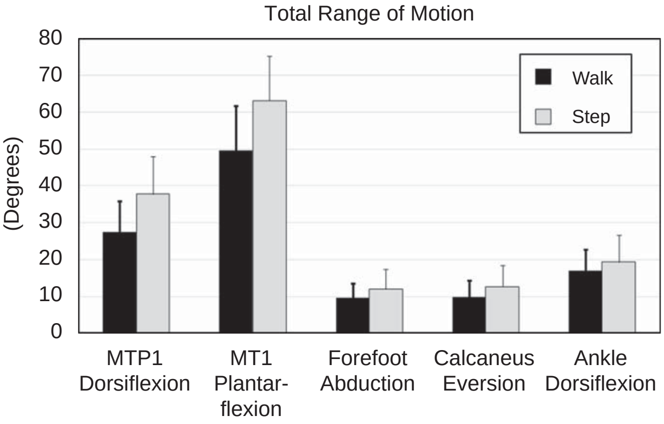

Fig. 4. All subjects demonstrated significantly greater total ROM of MTP1 dorsiflexion ($p<0.01$), ankle dorsiflexion ($p<0.01$) and forefoot abduction ($p=0.02$) during step descent compared to walking. Error bars indicate standard deviation.

Table 2
Summary of foot function index-revised (FFI-R) subscale and total score in patients with midfoot arthritis compared to matched control subjects, assessed as significant if $p<0.05$.

	Pain	Disability	Activity limitation	Psychosocial issues	Total score
Midfoot arthritis					
Mean	41	41	39	32	38
SD	13	11	19	12	11
Control subjects					
Mean	18	18	17	17	17
SD	2	2	0	0	1
p-Value	0.000	0.000	0.000	0.000	0.000
Effect size	1.82	2.10	1.16	1.28	1.82

Higher scores are indicative of more severe symptoms.

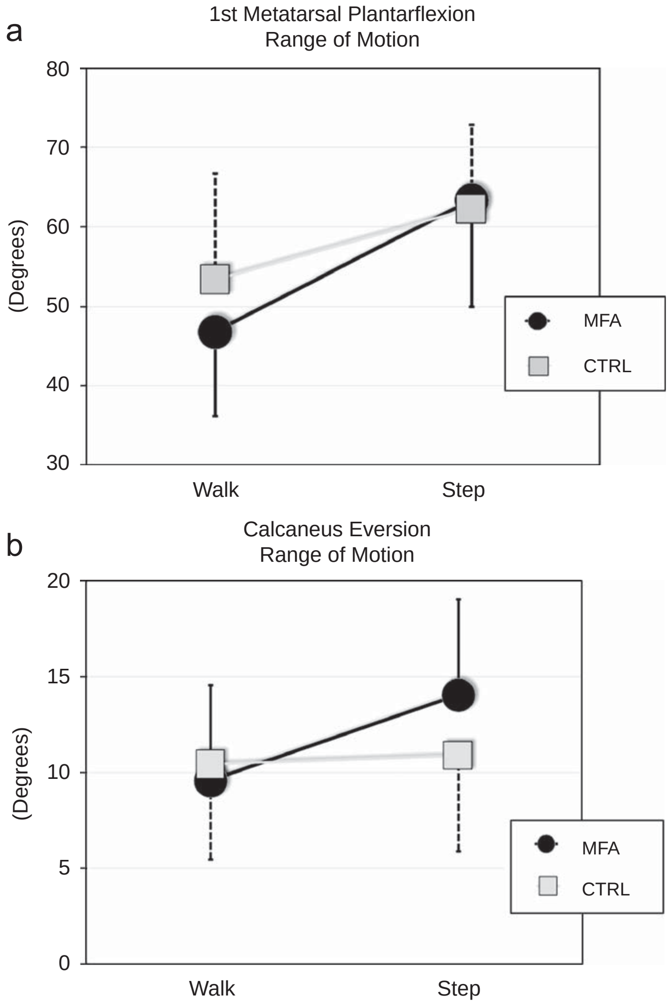

Fig. 5. (a) During walking, patients with midfoot arthritis showed significantly less MT1 plantarflexion excursion compared to control subjects. However, in the step task, both groups showed similar MT1 plantarflexion range of motion. Error bars indicate standard deviation. (b) During walking, patients with midfoot arthritis showed similar calcaneus eversion excursion compared to control subjects. However, in the step task, patients with midfoot arthritis showed significantly more calcaneus eversion excursion compared to control subjects. Error bars indicate standard deviation.

showed similar calcaneus eversion ROM compared to control subjects (Fig. 5b). However, in the step task, patients with midfoot arthritis showed significantly greater calcaneus eversion ROM compared to control subjects ($p = 0.03$).

4. Discussion

When compared to level walking, step descent required greater MTP1dorsiflexion, MT1 plantarflexion, ankle dorsiflexion, calcaneus eversion and forefoot abduction than walking, in both, study and control groups. In addition, step descent also necessitated greater ROM of MTP1dorsiflexion, ankle dorsiflexion and forefoot abduction. A key finding of this study, with potential clinical ramifications, is that patients with midfoot arthritis responded differently to the step task compared to control subjects in terms of MT1 and calcaneus eversion ROM. Increased MT1 plantarflexion and calcaneal eversion ROM in the step activity was noted in patients with midfoot arthritis. These patterns of segmental foot motion may be associated with concomitant articular stress and evolution of symptoms in patients with midfoot arthritis.

Patients with midfoot arthritis demonstrated significant limitations in self-reported foot function, reflected as a reduction in their FFI-R score compared to matched controls. The difference in FFI-R score between patients with midfoot arthritis and matched control subjects was driven largely by the presence of pain (effect size $= 1.82$) and activity limitation (effect size $= 1.16$), in agreement with previous reports of patients with midfoot arthritis. (Teng et al., 2002; Jung et al., 2007) Our cohort of patients with midfoot arthritis revealed a predominance of female patients compared to male (28/30). The gender distribution of our study sample reflects that of the demographic typically affected by midfoot arthritis and reported by previous authors (Davitt et al., 2005; Jung et al., 2007). The gender distribution of our study sample is also similar to previous reports of patients with rheumatoid arthritis (de P Magalhaes et al., 2006) in which women constituted 65–85% of the study sample. Based on the literature (Hardcastle et al., 1982), we expected that the majority of our patients would present with post-traumatic midfoot arthritis. Contrary to this expectation, none of our patients recalled a major traumatic event leading to their midfoot symptoms. A follow-up review of the more recent literature revealed that our study sample is similar in terms of etiology and patient demographics, to that reported in more recent cohorts (Davitt et al., 2005; Jung et al., 2007). The absence of major trauma combined with the gender distribution, may implicate the potential role of chronic increased joint loads sustained with poor footwear choices (Yu et al., 2007) in the development and progression of midfoot arthritis.

Patients with midfoot arthritis often identify stair descent as being particularly problematic. Question 18 of the FFI-R specifically addresses difficulty during descending stairs. ("During the past week, how much difficulty did your foot problems cause you descending stairs".) In agreement with the clinical impression, 80% (24/30) patients with midfoot arthritis versus 3% of control subjects (1/20) reported mild, moderate or severe pain on stair descent. The kinematic findings of this investigation indicate that step descent requires greater MTP1 dorsiflexion, MT1 plantarflexion, ankle dorsiflexion, calcaneus eversion and forefoot abduction than walking. In addition, step descent also necessitates greater ROM of MTP1 dorsiflexion, ankle dorsiflexion and forefoot abduction. For patients with midfoot arthritis, independently or in combination, these motions may contribute to abnormal patterns of articular stress and thus provoke symptoms in patients with midfoot arthritis.

The increase in sagittal plane ankle motion noted during step descent in the current study is in agreement with previous reports of increased ankle dorsiflexion during stair descent (Moseley et al., 2003). The increased kinematic demands may be particularly important in patients with arthritis of the foot because patients may approximate end range of joint motion and consequently sustain high articular stress. The increases in forefoot abduction and calcaneal eversion reported in the current study are novel findings and have not been previously reported in the literature. Forefoot abduction and calcaneal eversion are associated with an unlocked midfoot (Blackwood et al., 2005). In an unlocked midfoot, there may be less reliance on articular mechanisms for stability, thus necessitating increased muscle and ligamentous support. Over time, failure of soft tissues may contribute to symptoms in patients with foot pathology (Tome et al., 2006).

A key finding of this study was that patients with midfoot arthritis responded differently to the step task compared to control subjects in terms of MT1 plantarflexion and calcaneus eversion range of motion. During walking, patients with midfoot arthritis demonstrated significantly less MT1 plantarflexion ROM compared to control subjects. The reduction in MT1 plantarflexion range of motion may be analogous to the reduction in knee flexion

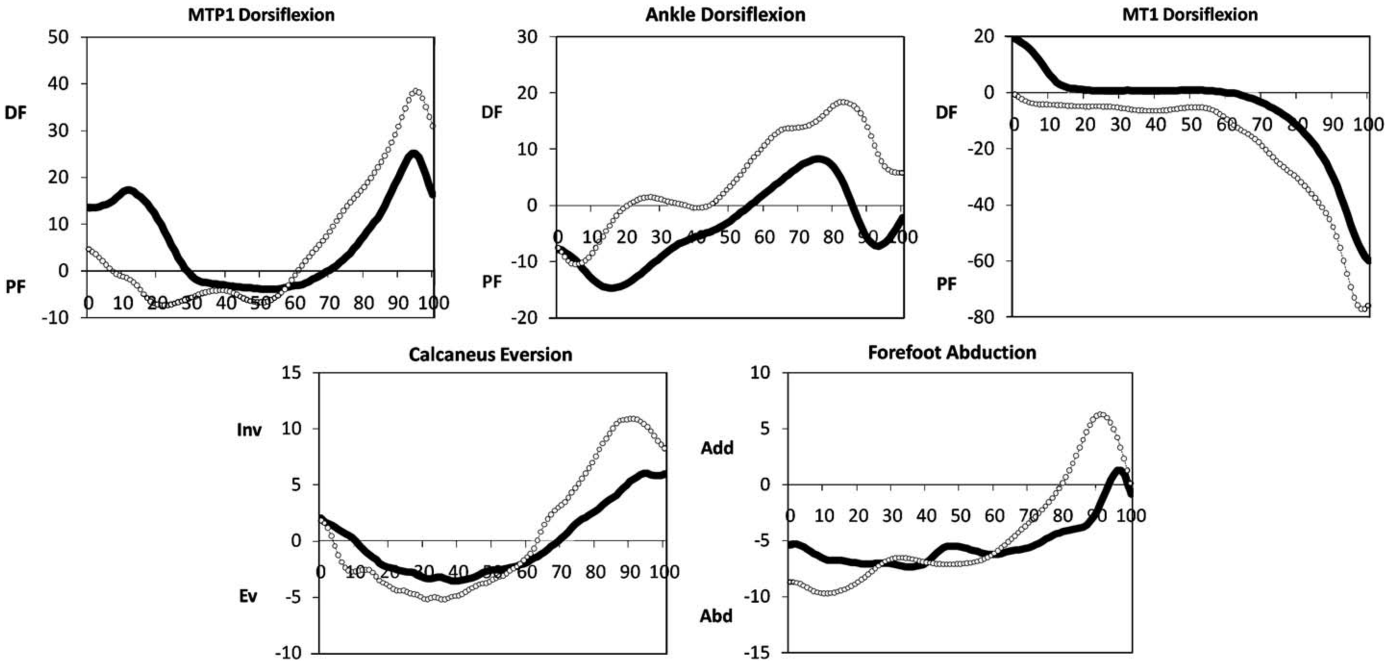

Fig. 6. Representative kinematic data from a single patient with midfoot arthritis during the walking (black line) and step descent (closed circles) tasks, normalized to 100% stance. Positive values indicate dorsiflexion, inversion and adduction in degrees.

demonstrated by patients with patellofemoral pain during walking (Powers et al., 1999). At the knee joint, the reduction in knee flexion reflects the use of a "stiffening" strategy and may be indicative of the patients' attempt to reduce compressive loads across the patellofemoral joint (Heino Brechter and Powers, 2002). Similarly, in patients with midfoot arthritis, the reduction in MT1 motion may be a strategy to limit articular stress at the tarsometatarsal joints because the MT1 forms the distal part of the tarsometatarsal articulation. In the step task, however, both groups showed similar MT1 plantarflexion range of motion. (Fig. 5a) The inability to modulate MT1 plantarflexion ROM during the step task may contribute to pain elicited during the task. The increased range of MT1 motion in step descent compared to walking in patients with midfoot arthritis may be indicative of loss of midfoot stability, evident only in more challenging non-gait activities.

During walking, patients with midfoot arthritis showed similar calcaneus eversion ROM compared to control subjects (Fig. 5b). However, in the step task, patients with midfoot arthritis showed significantly more calcaneus eversion ROM compared to control subjects. Calcaneal eversion has been postulated to 'unlock' the transverse tarsal joints (Blackwood et al., 2005). Consequently, increased calcaneal eversion ROM may allow greater midfoot and MT1 mobility. The increased MT1 mobility, in turn, may alter tarsometatarsal stress. The increase in calcaneal eversion seen in patients with midfoot arthritis during the step task may reflect patients' inability to modulate joint ROM during more challenging tasks, which in turn may contribute to tarsometatarsal articular stress and symptoms (Fig. 6).

One potential limitation of this study is the contention that step descent is not equivalent to stair descent. For the purposes of this study, we sought to recreate the task that elicits patients' symptoms without exposing patients to potentially harmful levels of load and the attendant risk of worsening symptoms. All subjects in the current cohort were able to complete the step descent task without reporting an acute increase in pain. Another potential limitation may be that *in vivo* kinematics is an indirect measure of articular stress. Errors due to soft tissue tracking are not accounted for in this study. While increasing evidence incriminates articular mechanics in the initiation and progression of osteoarthritis, (Andriacchi and Mundermann, 2006) and interventions designed for arthritis are often hypothesized to act by favorably influencing articular stress, quantitative data elucidating the relationship between *in vivo* kinematics and tarsometatarsal articular stress are lacking. Future studies exploring the relationship between *in vivo* foot kinematics and their articular consequences are indicated and underway in our laboratories.

Conflict of interest

We, the authors of this manuscript, affirm that we have no financial affiliation or involvement with any commercial organization that has a direct financial interest in any matter included in this manuscript except as cited in the manuscript.

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Appendix A. Supporting Information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jbiomech.2009.02.006.

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