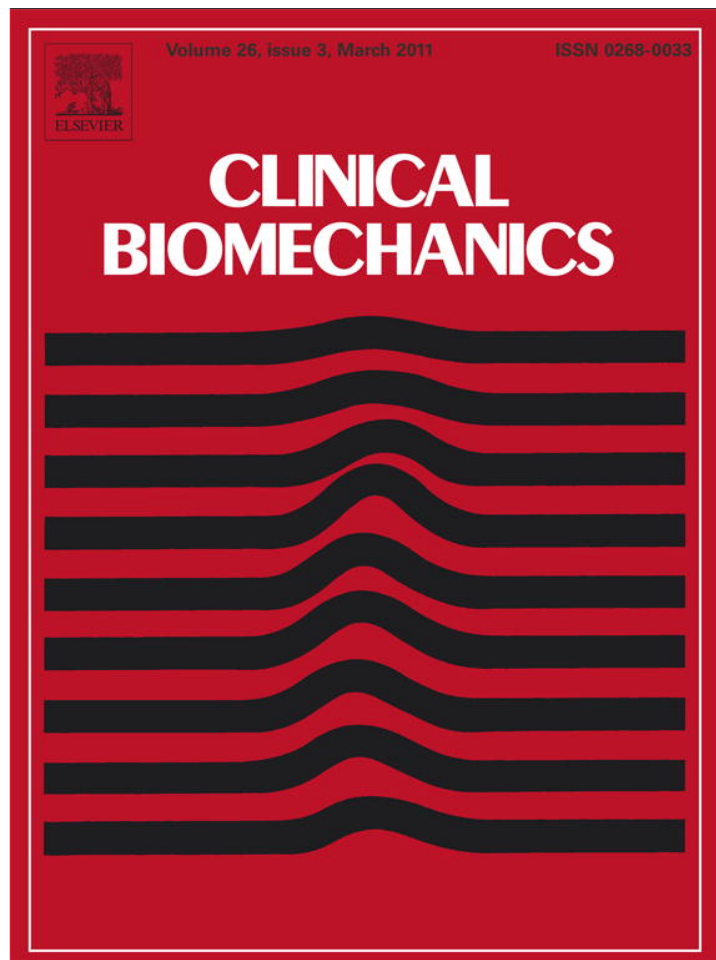


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The effect of arch height on kinematic coupling during walking^{☆,☆☆}

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ABSTRACT

The purpose of the current study was to assess kinematic coupling within the foot in individuals across a range of arch heights. Seventeen subjects participated in this study. Weight-bearing lateral radiographs were used to measure the arch height, defined as angle between the 1st metatarsal and the calcaneus. A kinematic model including the 1st metatarsal, lateral forefoot, calcaneus and tibia was used to assess foot kinematics during walking. Four coupling ratios were calculated: calcaneus frontal to forefoot transverse plane motion (Calcaneal EV/Forefoot AB), calcaneus frontal to transverse plane motion (Calcaneus EV/AB), forefoot sagittal to transverse plane motion (Forefoot DF/AB), and 1st metatarsal sagittal to transverse plane motion (1st Metatarsal DF/AB). Pearson product moment correlations were used to assess the relationship between arch height and coupling ratios. Mean (SD) radiographic arch angles of 129.8 (12.1) degrees with a range from 114 to 153 were noted, underscoring the range of arch heights in this cohort. Arch height explained approximately 3%, 38%, 12% and 1% of the variance in Calcaneal EV/Forefoot AB, Calcaneus EV/AB, Forefoot DF/AB and 1st Metatarsal DF/AB respectively. Calcaneal EV/Forefoot AB, Calcaneus EV/AB, Forefoot DF/AB and 1st Metatarsal DF/AB coupling ratios of 1.84 ± 0.80 , 0.56 ± 0.35 , 0.96 ± 0.27 and 0.43 ± 0.21 were noted, consistent with the twisted foot plate model, windlass mechanism and midtarsal locking mechanisms. Arch height had a small and modest relationship with kinematic coupling ratios during walking.

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1. Introduction

Arch height has been identified as a potential risk factor predisposing to musculoskeletal injury (Kaufman et al., 1999; Levy et al., 2006). However, recent prospective studies have found limited evidence supporting this contention (Knapik et al., 2009; Michelson et al., 2002).

In an attempt to uncover specific mechanisms by which arch height influences walking mechanics and possible risk of musculoskeletal injury, studies have examined kinematic coupling (Chang et al., 2008; Eslami et al., 2007; Pohl et al., 2007). Kinematic coupling reflects inter-segment coordination, and can be quantified using a coupling ratio derived from angle–angle plots (DeLeo et al., 2004; Nawoczenski et al., 1998). Using these methods, several studies have shown that individuals with high arches demonstrate lower calcaneal eversion–tibial internal rotation coupling ratio (Nawoczenski et al.,

1998; Nigg et al., 1993; Williams et al., 2001). These findings are in agreement with the theory that a high arch alters the orientation of the subtalar joint axis, resulting in a kinematic pattern that favors tibial rotation over calcaneal eversion (Nawoczenski et al., 1998; Sarrafian, 1993).

In addition to its effect on the subtalar joint, arch height may influence kinematic coupling within the segments of the foot (Chang et al., 2008; Sarrafian, 1987). Mechanical analogs, such as the twisted foot plate model (Sarrafian, 1987), and the midtarsal locking mechanism (Elftman, 1960) and the windlass (Hicks, 1954), provide the theoretical basis for kinematic coupling in foot. In individuals with high arches, increased calcaneal inversion ("twisting" of the foot plate) may be accompanied by increased forefoot inversion, adduction and plantarflexion. Conversely, in individuals with low arches, calcaneal eversion ("untwisting" of the foot plate) may be accompanied by forefoot eversion, abduction and dorsiflexion. Further, Elftman's model of midtarsal locking suggests that calcaneal inversion (high arch) would "lock" the midfoot and lead to decreased forefoot motion, while calcaneal eversion (low arch) would unlock the midfoot and result in increased forefoot motion. Elftman's theory of midtarsal locking suggests that increasing arch height may influence the relative amounts (ratio) of calcaneal eversion to forefoot abduction.

Arch lowering is accompanied by calcaneal eversion, which in turn, has been postulated to decrease the inclination of the subtalar

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joint axis of rotation (Arangio et al., 1998; Blackwood et al., 2005). Secondary to the change in subtalar axis orientation, increased forefoot dorsiflexion and decreased forefoot adduction (Van Boerum and Sangeorzan, 2003) have been predicted in individuals with low arches. Conversely, individuals with high arch feet may demonstrate a greater proportion of forefoot adduction compared to forefoot plantarflexion, evidenced as an altered coupling ratio and indicative of early activation of the windlass mechanism. These alterations in kinematic coupling (ratio of forefoot dorsiflexion to abduction, ratio of 1st metatarsal dorsiflexion to abduction) may influence the ability of the foot to form a rigid lever at push off and therefore have significant functional consequences. The increase in sagittal plane motion and concomitant decrease in transverse plane motion, may be evidenced as an altered coupling ratio and suggest that the ability of the windlass mechanism to produce a stable foot configuration at push off is compromised in low arched feet.

Recent studies evaluating kinematic coupling in the foot have found evidence supporting forefoot to calcaneus coupling (forefoot abduction/calcaneal eversion, forefoot dorsiflexion/calcaneal eversion) (Eslami et al., 2007; Pohl et al., 2006). However, these studies evaluated subjects with normal arch structure, and assessed kinematic coupling during barefoot running (Pohl et al., 2006) or running in sandals (Eslami et al., 2007). Their extrapolation to individuals with high or low arches, and during walking may not be valid.

Studies evaluating coupling during walking have found robust forefoot to calcaneus coupling, quantified using cross-correlation ($r=0.91$) (Pohl et al., 2007) and vector coding (Chang et al., 2008). However, these studies have been restricted to subjects with normal arch structure (Pohl et al., 2007) or small sample size (Chang et al., 2008). Lastly, all the studies evaluating kinematic coupling in the foot have modeled the forefoot as a single segment (Chang et al., 2008; Eslami et al., 2007; Pohl et al., 2006, 2007; Pohl and Buckley, 2008). The validity of modeling the forefoot as a single rigid body has been recently called into question (Okita et al., 2009).

While theoretical and epidemiological studies suggest that arch structure may influence kinematic coupling in the foot during walking, objective evidence examining the effect of arch height on coupling during walking is limited, particularly at terminal stance when the foot functions as a rigid level for push off. Therefore the purpose of the current study was to assess kinematic coupling within the foot in individuals across a range of arch heights. These results may provide valuable insights regarding inter-segment coordination, and possible mechanisms by which arch height may contribute to injury risk.

2. Methods

2.1. Subjects

Seventeen physically active subjects (8 male, 9 female) between the ages of 18 and 36 with no current history of lower extremity pain were recruited to participate in this study. Subjects were on average 25 (4.5) years old with a mean body mass and height of 74 (14) Kg and 1.7 (0.1) m respectively. To ensure that subjects with a wide range of arch heights participated, only subjects with self reported high or low arches were recruited. Subjects reported no history of lower extremity injury including stress fractures, plantar fasciitis or knee injuries. Informed consent was obtained from all subjects prior to participation. All procedures were reviewed and approved by University of Iowa Human Subjects Office, Institutional Review Board-01 (Biomedical).

2.2. Sample size estimates

Sample size was estimated using custom software (<http://www.stat.uiowa.edu/~rlenth/Power>). For $\alpha=0.05$ and $(1-\beta)=0.80$, a sample size of 16 subjects would be required (1 predictor, error SD = 1, arch height SD = 10, effect size of 3°). Given a sample size of 16

subjects, Pearson product moment correlation coefficient, r ; $df=14$, $\alpha=0.05$, $r_{crit}=0.497$ (Portney and Watkins, 2000). Correlation values of less than 0.5 were deemed not of clinical significance and therefore, even if statistically significant were not addressed as relevant.

2.3. Radiographs

Antero-posterior and lateral weight-bearing radiographs of the index foot were used to determine the static foot alignment for each subject (Saltzman et al., 1994, 1995), as well as allow anatomically based alignment of local coordinate systems (Kidder et al., 1996). The angle between the dorsal surface of the 1st metatarsal and the inferior border of the calcaneus (Saltzman et al., 1995) was used to represent arch height (Fig. 1).

2.4. Procedure

A five-segment model including the hallux, 1st metatarsal, lateral forefoot, calcaneus and tibia was used to assess foot kinematics during walking. Three infrared light emitting diodes (IREDs) were tracked (Optotrak 3020, Northern Digital Inc. Waterloo, Canada) as subjects walked at a controlled speed of 0.78 statures/second.

Details related to the model have been presented previously (Rao et al., 2007) and are summarized here briefly. Calcaneal motion was assessed using two markers on the lateral calcaneus proximal to the calcaneal fat pad, and one on the posterior aspect of the calcaneus. Forefoot motion was determined by markers on the proximal and distal 2nd metatarsal and the proximal 5th metatarsal. Motion of the 1st metatarsal was tracked with a lightweight marker triad mounted on the 1st metatarsal, medial to the extensor hallucis longus tendon (Fig. 2). Hallux motion was determined using an IRED triad with a rigid dorsal cuff and elastic band to secure it to the proximal phalanx. Similar to the approach developed by Kidder et al., a digitizing process in conjunction with lateral and AP x-rays of the foot was used to identify the location of underlying bony geometry relative to each segment's marker triad (Kidder et al., 1996). For the 1st metatarsal and forefoot segments the local coordinate system was adjusted to align with the long axis of the 1st and 2nd metatarsals respectively (Fig. 2). For the calcaneal segment the AP axis was aligned from the posterior heel to the midpoint of the midfoot and inclined in the sagittal plane to match the calcaneal inclination angle (Saltzman et al., 1995). The calcaneal



Fig. 1. Lateral weightbearing radiographs from individuals with low arch (top) and high arch (bottom), demonstrating range of arch heights tested.

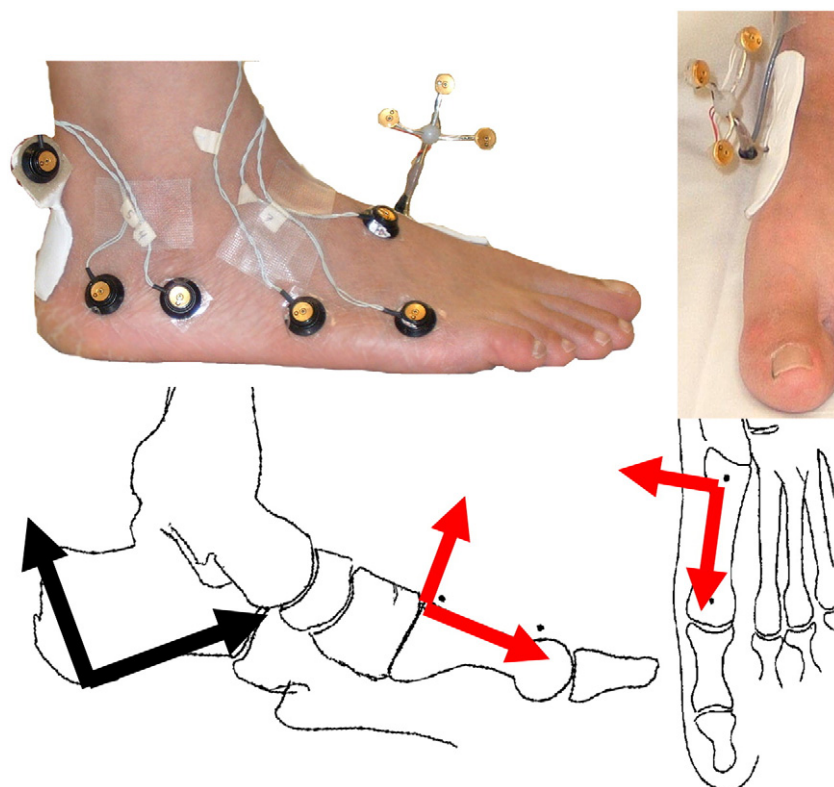


Fig. 2. Kinematic model used to track calcaneus, forefoot and 1st metatarsal segments. Infrared emitting diodes were also placed on the hallux and tibia (not pictured).

bisector was palpated manually by a single tester (JMW), and defined using two radio-opaque beads. The vertical axis was aligned parallel to the calcaneal bisector line in the frontal plane, with the medio-lateral axis orthogonal to the other two. Additional details are illustrated in a Supplementary Figure.

Kinematic data was collected at 120 Hz and low pass filtered using a 6 Hz cutoff frequency. Visual3D software (C-Motion Inc.) was used to determine segment and joint angles and velocities using an Euler angle approach. Motion of the distal segment was expressed relative to the proximal segment for the following segments: calcaneus relative to tibia, forefoot relative to calcaneus, 1st metatarsal relative to calcaneus, and hallux relative to 1st metatarsal. Vertical ground reaction forces collected via a Kistler force plate (Kister Instrument Corp., Model 9865B) at a sampling rate of 360 Hz, synchronized with kinematic data and were used to determine vertical ground reaction forces for normalization of kinematic data to 100% stance phase.

2.5. Timing

The angular velocity of 1st metatarsal sagittal plane motion, relative to the floor, and sagittal plane motion of the 1st metatarsal, relative to the calcaneus, were used to determine the interval over which kinematic coupling was assessed. Peak arch elongation (PAE) was defined as the maximally dorsiflexed position of the 1st metatarsal relative to the calcaneus during the stance phase of gait. The MINVEL point was identified as minima in forward rotation velocity of the 1st metatarsal relative to the floor. This interval was selected as it represents the portion of terminal stance during which the foot transitions to a rigid structure that allows for efficient propulsion during push-off (Leardini et al., 2007; Okita et al., 2009; Rao et al., 2007).

2.6. Data analysis

Coupling ratios were determined by plotting kinematics from PAE to MINVEL using an angle–angle plot. This was performed for each trial and

the slope of the linear regression line fit to the data for each individual trial was used to represent a coupling ratio for that trial (Nigg et al., 1993). The median value was used to represent the coupling ratio for each subject. A total of four coupling ratios were calculated: calcaneus frontal plane motion to forefoot transverse plane motion (Calcaneal EV/Forefoot AB), calcaneus frontal plane motion to calcaneus transverse plane motion (Calcaneus EV/AB), forefoot sagittal plane motion to forefoot transverse plane motion (Forefoot DF/AB), and 1st metatarsal sagittal plane motion to 1st metatarsal transverse plane motion (1st Metatarsal DF/AB). To ensure that the coupling ratio determined using linear regression was representative of the data a threshold for acceptance of the coupling ratio was set at an *r*-squared value of 0.75. This step was taken to guard against inappropriate representation of curvilinear data using a linear coupling ratio. In addition to using linear regression to determine coupling ratios, absolute change over the interval was also used to determine joint coupling. The total difference between maximum and minimum values (change over interval) from PAE to MINVEL was used, consistent with the work of others (Nawoczenski et al., 1998) to compare the similarity of the two methods. Coupling ratios less than one indicate that transverse plane motion was greater than motion in other planes. Mean and standard deviation values were calculated for coupling ratios. Pearson product moment correlation (*r*) was used to assess the relationship between coupling ratio and arch height, and to assess the relationship between coupling ratios calculated using two different methods (linear regression versus change over interval).

3. Results

3.1. Radiographic measures of arch height

Mean (SD) 1st metatarsal inclination was 26.5 (4.8) degrees with a range from 16.0 to 34.6° while calcaneal inclination angle had a range from 10.8 to 35.6 about a mean (SD) of 24.3 (8.1) degrees. This resulted in mean (SD) radiographic arch angles of 129.8 (12.1) degrees with a range from 114 to 153.

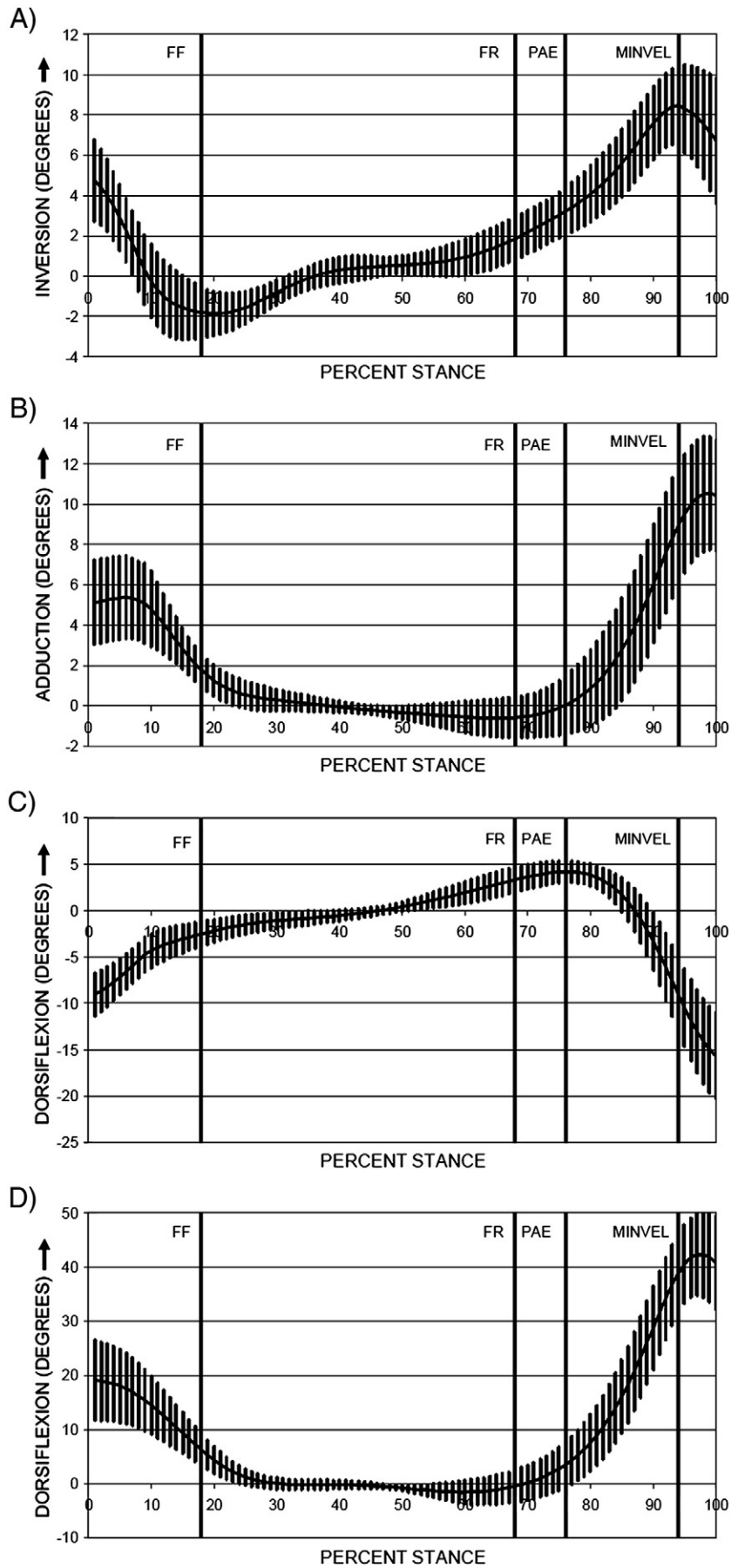


Fig. 3. Ensemble average ($\pm 1SD$) kinematics of A) frontal plane motion of the calcaneus relative to the tibia B) transverse plane motion of the forefoot relative to the calcaneus C) sagittal plane motion of the 1st metatarsal relative to the calcaneus and D) sagittal plane motion of the hallux relative to the 1st metatarsal during the stance phase of gait.

Table 1

Mean and standard deviation values (percent stance phase) for the timing of 1st metatarsal and arch kinematic events. (FF = Forefoot contact, FR = Forward rotation of 1st metatarsal, PAE = Peak Arch Elongation, MINVEL = minima in 1st metatarsal forward rotation velocity.)

Event	Mean	SD between subjects	SD within subject
FF	18.0	3.1	1.0
FR	67.7	3.2	1.7
PAE	76.2	3.3	1.3
MINVEL	94.1	1.4	0.7

3.2. Foot kinematics during walking

Time normalized kinematic patterns are presented in Fig. 3. The mean and standard deviation for the timing of these events are presented in Table 1.

3.3. Kinematic coupling

Representative data from five walking trials for each of the coupling ratios is depicted in Fig. 4. The association between methods of calculating coupling ratios was high (Table 2). Kinematic coupling over the PAE-MINVEL interval and its relationship to arch height is summarized in Table 2. Arch height explained approximately 3%, 38%, 12% and 1% of the variance in Calcaneal EV/Forefoot AB, Calcaneus EV/AB, Forefoot DF/AB and 1st Metatarsal DF/AB respectively. Due to non-linear coupling relationships for several subjects, Calcaneus EV/AB ratio was only calculated for ten of the 17 subjects. Sample coupling relationships are depicted in Appendix 1.

4. Discussion

The findings of this study provide objective evidence demonstrating kinematic coupling within and between segments of the foot. The coupling ratios provide insight into the motions that result from action of the windlass mechanism at the end of the stance phase (PAE until MINVEL). Contrary to our expectations, arch height had a modest relationship with only the calcaneal EV/AB kinematic coupling ratio in the foot.

Consistent with the twisted foot plate model (Sarrafian, 1987) and previous reports (Carson et al., 2001; Chang et al., 2008; Hunt et al., 2001; Leardini et al., 2007; Okita et al., 2009; Rao et al., 2007), early calcaneal eversion was followed by gradual calcaneal inversion and progressive arch dorsiflexion (Fig. 3). In the interval from 1st metatarsal rotation (FR) to peak arch elongation (PAE), gradual dorsiflexion of the hallux and forefoot adduction, possibly due to loading of the plantar fascia, produced supination of the foot. Consistent with arch kinematics reported in this study, progressive loading of the plantar fascia, late in the stance phase, has been noted in *in vitro* testing (Erdemir et al., 2004).

At terminal stance, supination of the foot, evidenced as plantarflexion and adduction of the forefoot combined with inversion of the calcaneus, was noted (Fig. 3). This combination of motions occurred shortly after hallux dorsiflexion (Fig. 3), and may contribute to an articular configuration that allows sufficient foot rigidity to withstand the large loads experienced at push-off. This kinematic sequencing supports the theory that activation of the windlass mechanism and the midtarsal locking mechanism contributes to supination of the foot (Elftman, 1960; Hicks, 1954).

From PAE to MINVEL, a calcaneal eversion/forefoot abduction ratio of 1.62 was noted and indicates that calcaneal frontal plane motion predominated over forefoot transverse plane motion. Consistent with the midtarsal locking mechanism and recent evidence from normal

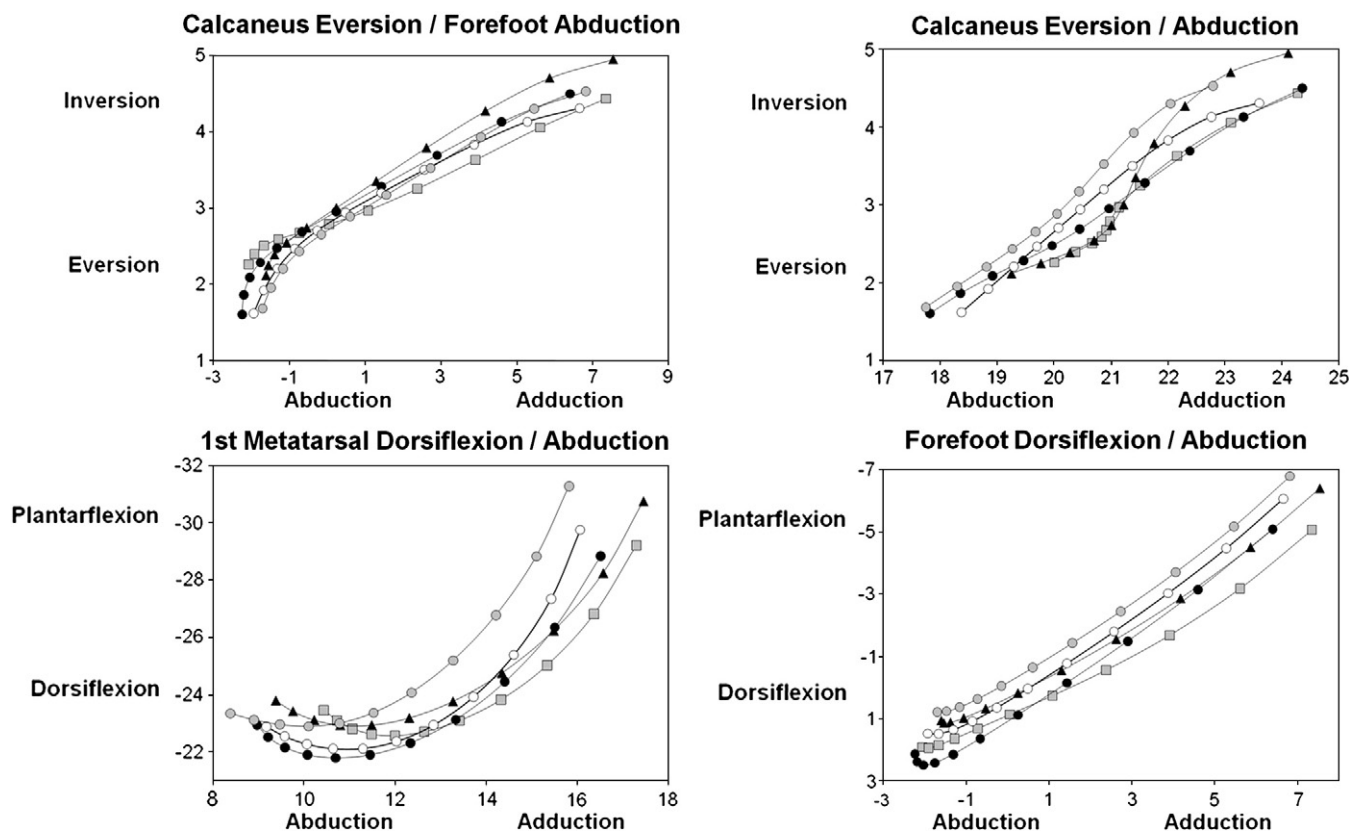


Fig. 4. Representative angle-angle plots for five trials from a single subject, used to calculate coupling ratio. All kinematics are expressed in degrees. Clockwise from top left: Calcaneal Eversion/Forefoot Abduction, Calcaneal Eversion/Abduction, Forefoot Dorsiflexion/Abduction, and 1st Metatarsal Dorsiflexion/Abduction.

Table 2

Mean (SD) values for both methods of calculating coupling ratios during the interval from PAE to MINVEL, the correlation between the two methods as well as the correlation between joint coupling as determined using linear regression and radiographic arch angle. Coupling ratio values less than one indicate that transverse plane motion predominates.

Comparison	Linear regression	Change over interval	Correlation between methods	Correlation with radiographic arch angle
Calcaneal EV/Forefoot AB	1.62 (0.64)	1.84 (0.80)	0.98	0.17
Calcaneus EV/AB	0.28 (0.44)*	0.56 (0.35)	0.71	−0.62
Forefoot DF/AB	0.96 (0.26)	0.96 (0.27)	0.99	0.34
1st Metatarsal DF/AB	0.44 (0.24)	0.43 (0.21)	0.99	−0.12

*n = 10.

arch subjects during running (Pohl et al., 2007), calcaneal eversion was related to increasing forefoot abduction, while calcaneal inversion was noted with increasing forefoot adduction (Fig. 4).

Motion of the 1st metatarsal relative to the calcaneus, while demonstrating characteristic adduction and plantarflexion produced by the windlass mechanism, was found to exhibit a coupling ratio considerably lower than that found in the forefoot (Table 2, Fig. 3). In the forefoot, we found about a one-to-one ratio between plantarflexion and adduction, while a 0.5 to 1 ratio was seen in the 1st metatarsal. These different ratios may be accounted for by the geometry of the calcaneocuboid versus the talo-navicular joints, and the consequent obliquity of joint axes (Hicks, 1953).

Coupling between calcaneus inversion and adduction produced inconsistent results (Appendix 1). Due to non-linear relationships, coupling ratios were not determined for seven individuals. In the subjects where a coupling ratio was calculated, a moderate association between arch height and coupling ratio was observed. Consistent with our hypotheses, we found decreased coupling ratios in lower arched individuals, possibly due to lowering of the subtalar joint axis (Nawoczenski et al., 1998).

It was anticipated that changes in foot structure associated with arch height would result in altered coupling ratios. However, of the relationships explored, our findings revealed that only calcaneal coupling ratios were associated with arch height. These findings may suggest that, in asymptomatic individuals, arch height plays a modest role in kinematic coupling during walking.

The findings of this study must be interpreted in the context of its limitations. Because only individuals without current lower extremity problems were included in the study, the study sample may only represent individuals who are able to successfully accommodate to their foot structure. Further, the study sample comprised a young active population and these results may not be generalizable to older or more sedentary individuals. Additional studies are needed to assess kinematic coupling in the foot in higher demand activities and in individuals with and without symptoms.

In conclusion, the chief findings of this study identified kinematic coupling relationships, occurring at terminal stance when the foot functions as a rigid level for push-off. These kinematic coupling ratios are consistent with the twisted foot plate model, windlass mechanism and midtarsal locking mechanisms. Contrary to our expectations, arch height had a small and modest relationship with kinematic coupling ratios in the foot.

Supplementary materials related to this article can be found online at doi:10.1016/j.clinbiomech.2010.10.005.

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