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The effect of stride length on the dynamics of barefoot and shod running

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ABSTRACT

A number of interventions and technique changes have been proposed to attempt to improve performance and reduce the number of running related injuries. Running shoes, barefoot running and alterations in spatio-temporal parameters (stride frequency and stride length) have been associated with significant kinematic and kinetic changes, which may have implications for performance and injury prevention. However, because footwear interventions have been shown to also affect spatio-temporal parameters, there is uncertainty regarding the origin of the kinematic and kinetic alterations. Therefore, the purpose of this study was to independently evaluate the effects of shoes and changes in stride length on lower extremity kinetics. Eleven individuals ran over-ground at stride lengths ±5 and 10% of their preferred stride length, in both the barefoot and shod condition. Three-dimensional motion capture and force plate data were captured synchronously and used to compute lower extremity joint moments. We found a significant main effect of stride length on anterior–posterior and vertical GRFs, and sagittal plane knee and ankle moments in both barefoot and shod running. When subjects ran at identical stride lengths in the barefoot and shod conditions we did not observe differences for any of the kinetic variables that were measured. These findings suggest that barefoot running triggers a decrease in stride length, which could lead to a decrease in GRFs and sagittal plane joint moments. When evaluating barefoot running as a potential option to reduce injury, it is important to consider the associated change in stride length.

1. Introduction

Given the popularity of running, a number of interventions and technique changes have been proposed to attempt to improve performance and reduce the number of running related injuries. Altering running conditions can lead to kinematic and kinetic changes that may optimize muscle/tendon function and/or reduce stress on biological tissues (e.g. tendon, ligament, cartilage). Running shoes, barefoot running (Altman and Davis, 2012) and alterations in spatio-temporal parameters (stride frequency and stride length) (Derrick et al., 1998; Heiderscheit et al., 2011; Hobara et al., 2011; Lafortune et al., 1996; White and Lage, 1993) have been associated with significant kinematic and kinetic changes, which may have implications performance and injury risk. However, some interventions, such as footwear, have been shown to also affect spatio-temporal parameters (Altman and Davis, 2012), which leads to uncertainty regarding the origin of the kinematic and kinetic alterations. Therefore, the aim of this study was to systematically manipulate shoe conditions (barefoot versus shod) and stride length in order to understand how these conditions independently affect running dynamics.

Several previous studies have evaluated kinetic differences between barefoot and shod running, yet there is no consensus on potential differences in ground reaction forces (GRFs). For example, Divert et al. (2005), Lieberman et al. (2010) and Squadrone and Gallozzi (2009) report decreased impact forces in the barefoot condition, whereas De Wit et al. (2000) and Dickinson et al. (1985) found no difference in impact peaks between the barefoot and shod running, and Komi et al. (1987) found greater impact peaks in the barefoot condition. Varied results have also been reported for the differences in the GRF active peak between barefoot and shod running. Braunstein et al. (2010), Divert et al. (2005) and Kerrigan et al. (2009) report greater active peaks in the shod condition, while De Wit et al. (2000) and Squadrone and Gallozzi (2009) found no difference in the GRF active peak

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between barefoot and shod running. Potential differences in the anterior–posterior GRF components are also unclear; with Divert et al. (2005) reporting greater propulsive forces in the barefoot condition and De Wit et al. (2000) finding no difference in either braking or propulsive force between conditions.

One possible reason for the discrepancy in GRFs between barefoot and shod running may be differences in kinematic alterations when individuals run barefoot. While shoes offer an obvious protective benefit, the elevated and cushioned heel of modern running shoes leads many individuals to adopt a rear-foot strike pattern, which may increase collision forces (Lieberman et al., 2010) and joint moments (Kerrigan et al., 2009). Alternatively, when running barefoot, individuals tend to have a decreased range of motion at the knee, ankle and hip (Jenkins and Cauthon, 2011); a more plantarflexed position at ground contact (Divert, et al., 2005; Lieberman et al., 2010; Squadrone and Gallozzi, 2009); and a significantly shorter stride length as compared to the shod condition (De Wit et al., 2000; Divert et al., 2005; Kerrigan et al., 2009; Komi et al., 1987; Lieberman, et al., 2010; Squadrone and Gallozzi, 2009). The change in stride length is of particular interest as it has both kinematic and kinetic implications.

While differences in running kinetics associated with barefoot and shod running have received considerable attention, the independent changes associated with running in shoes (versus barefoot) and stride length have not be evaluated. In a study of shod runners, Farley and Gonzalez (1996) have shown that peak vertical GRFs decreased significantly with decreases in stride length. Derrick et al. (1998) report that decreasing stride length in the shod condition resulted in decreased lower extremity joint moments, though no statistics are provided. Further, Kerrigan et al. (2009) found that peak lower extremity joint moments were reduced in barefoot running, but there was little correlation between the decreased stride length associated with the barefoot condition and the decreased joint moments. While studies have clearly shown that barefoot running results in reduced stride lengths relative to shod running, it remains unclear how these changes influence joint dynamics. Therefore, in this study we independently evaluated the effects of shoes and changes in stride length on lower extremity kinetics. We hypothesized that peak ground reaction forces and joint moments would not differ for conditions of similar stride length and running velocity, regardless if an individual was running in shoes.

2. Methods

Eleven healthy, physically active adults [6 men and 5 women, age: 29 ± 5.6 yr; height: 1.63 ± 0.12 m; mass: 62.6 ± 12.1 kg] participated in this study. Subjects were required to perform a minimum of 30 min of physical activity at least 5 days a week, and be free of musculoskeletal injury of the lower extremities or back. The University of Idaho's Institutional Review Board approved the protocol for this study, and written informed consent was obtained from each subject.

2.1. Experimental protocol

Subjects completed 2 testing sessions, which were separated by a minimum of 24 h. Subjects began each session with 5–10 min of easy running in order to warm-up and habituate to the runway. Session 1 was used to determine the subject's preferred running gait (i.e., self-selected stride length and running velocity) in both barefoot and shod conditions. For the baseline (preferred) conditions, stride length and running velocity were averaged from 5 trials. In Session 2, subjects ran with their stride length manipulated to ± 5 and 10% of their preferred shod stride length while barefoot and shod, for a total of 8 conditions. Both barefoot and shod stride length manipulations were based on the preferred shod condition so that in subsequent trials (e.g. +10%) the stride length was identical in both the barefoot and shod conditions. This allowed the effects of stride length and the shod/barefoot conditions to be independently evaluated. Additionally, all conditions in Session 2 were completed at the subject's preferred shod running velocity. In order to control running velocity, subjects matched their speed to a target on a motor driven pulley system that ran parallel to the runway. Stride length was controlled by having subjects match step length to strips of tape placed along the runway (Fig. 1). In Session 2, subjects performed 10 trials of each condition and 5 trials that were within 2% of the desired stride length and 5% of the desired running velocity were used for analysis.

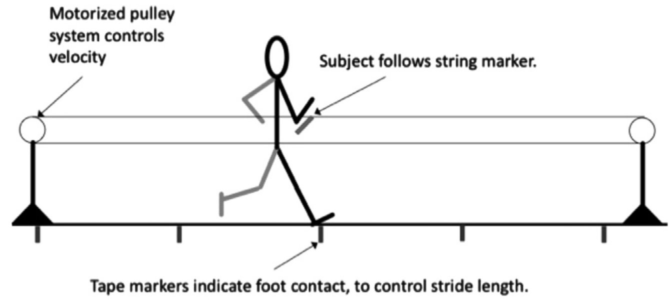

Fig. 1. The experimental set up for stride length manipulation trials.

2.2. Kinetics

3-dimensional motion analysis and GRF data were captured as subjects ran over a 15 m runway with a force plate (AMTI, Waterton, MA) embedded at 10 m. 16 retro-reflective markers were affixed with double-sided tape to specific landmarks according to the Modified Helen Hayes Marker set (Kadaba et al., 1990). Markers were placed on the right and left anterior and posterior superior iliac spines, lateral mid-thigh, lateral femoral epicondyle, lateral mid-shank, lateral malleolus, second metatarsal head and calcaneus. For the shod condition, heel and toe markers were placed on the shoes at the positions best aligning with the anatomical landmarks. Height, weight, leg length, and widths of the ankles and knees were measured for appropriate anthropometric scaling. 3-dimensional positions of each marker were captured at 250 Hz via a Vicon MX motion analysis system (Vicon, Oxford Metrics Ltd., UK). Marker trajectory data were filtered using a Woltring filtering routine with a predicted mean square error value of 4 mm^2. The three orthogonal components of the GRF data were recorded at 1000 Hz from the force plate in synchrony with the motion capture data. Force plate data were low-pass filtered at 30 Hz using a second-order Butterworth filter before being down-sampled and combined with the motion capture data.

Stride length was measured as the horizontal distance between ipsilateral heel marker minima. Running velocity was calculated as the horizontal displacement of each anterior superior iliac spine (ASIS) marker through the capture volume divided by the corresponding time. Running velocity was calculated for both the right and left ASIS markers and averaged. Joint moments were calculated for each trial via an inverse-dynamics model implemented in Vicon Plug-In Gait.

2.3. Statistics

Statistical differences in peak kinetic parameters were determined using a repeated-measures General Linear Model in SPSS (IBM, Armonk, NY). When a significant effect was identified, a post hoc Bonferroni pairwise comparison was performed to determine which conditions were significantly different. Statistical significance was defined as $P < 0.05$.

3. Results

3.1. Preferred conditions

Subjects adopted a significantly shorter stride length and decreased running velocity in the preferred barefoot condition ($P < 0.05$) (Table 1) compared to the preferred shod condition. There were no significant differences between the barefoot and shod condition for any of the kinetic parameters that were measured (Table 2).

3.2. Altered stride length conditions

There was a significant main effect for the relationship between stride length and the anterior–posterior GRF and vertical GRF ($P < 0.05$) (Fig. 2). There was also a significant main effect for the relationship between stride length and sagittal plane ankle and knee moments ($P < 0.05$) (Fig. 3). Peak values for GRFs and joint moments are shown in Fig. 4. Pairwise comparisons showed that

Table 1
Preferred stride length and running velocity for barefoot and shod running.

Condition	Stride length (m)	Velocity (m/s)
Barefoot	2.13 ± 0.31*	3.18 ± 0.48*
Shod	2.32 ± 0.36	3.31 ± 0.47

Mean (SD) values for preferred stride length and running velocity for barefoot and shod running.

* Indicates significant difference between barefoot and shod conditions ($p < 0.05$).

peak vertical GRFs in the shod −10%, −5% and +10% conditions differed significantly from the preferred shod condition ($P=0.007$, $P=0.023$ and $P=0.029$ correspondingly), and peak vertical GRFs in the barefoot +5% and +10% conditions were significantly greater than the preferred barefoot condition ($P=0.033$ and $P=0.004$ correspondingly) (Table 2). Peak anterior–posterior GRF in the shod +10% condition was significantly greater than the preferred shod condition ($P=0.030$), and peak anterior–posterior GRFs in the barefoot +5% and +10% conditions were significantly greater than the preferred barefoot condition ($P=0.010$ and $P=0.001$ correspondingly) (Table 2). In the sagittal plane, knee and ankle peak joint moments in the +10% condition were significantly greater than the preferred condition for both barefoot and shod running (Knee: $P=0.018$ and $P=0.010$ correspondingly, Ankle: $P=0.013$ and $P=0.017$ correspondingly) (Table 2). In the frontal and transverse planes there were no significant differences between any of the stride length conditions for any of the kinetic parameters that were measured. When subjects ran at an identical stride length (e.g. −10%) in both the barefoot and shod condition there were no significant differences in any of the kinetic parameters that were measured.

4. Discussion

The goal of this study was to independently evaluate the effects of shoes and changes in stride length on lower extremity kinetics. Few studies have evaluated the effect of either stride length (Derrick et al., 1998; Heiderscheit et al., 2011; Hobara et al., 2011) or shoes (Bonacci et al., 2013; Kerrigan et al., 2009) on running kinetics. Because barefoot running leads to a decrease in stride length, the results of studies comparing barefoot and shod running are complicated and it remains uncertain if stride length, shoes or other factors lead to altered kinetics. To the best of our knowledge this is the first study to independently evaluate the effect of shoes and stride length on running kinetics.

The results of this study support our hypothesis that peak GRFs and joint moments would not differ for conditions of similar stride-length and running velocity, regardless if an individual is wearing shoes. Further, we found that stride length has a significant effect on GRFs and joint moments. Specifically, anterior–posterior and vertical GRFs, and sagittal plane knee and ankle joint moments increased with increasing stride length in both the barefoot and shod conditions.

The increased sagittal plane joint moments that were observed with increases in stride length can be explained, in part, by changes in the moment arm relative to the resultant GRF. The moment arm of the GRF depends on the point of force application relative to a joint axis of rotation and the orientation of the ground reaction force vector. With a decrease in stride length the heel is located more underneath the COM at initial contact and there is a decrease in peak hip and knee flexion (Heiderscheit et al., 2011), which would act to reduce moment arms to the GRF (Derrick et al., 1998). Further, though information regarding changes in stride

Table 2
Kinetic parameters.

	−10%		−5%		Preferred		+5%		+10%	
	BF	Shod	BF	Shod	BF	Shod	BF	Shod	BF	Shod
Joint moments (N m kg^{-1})										
Ankle dorsiflexion	2.59 (0.33)	2.64 (0.36)	2.55 (0.37)	2.58 (0.41)	2.60 (0.45)	2.64 (0.36)	2.85 (0.43)	2.82 (0.49)	3.01 (0.54)^	2.97 (0.46)^
Ankle adduction	0.21 (0.12)	0.17 (0.15)	0.21 (0.08)	0.17 (0.14)	0.22 (0.13)	0.14 (0.06)	0.24 (0.13)	0.19 (0.15)	0.26 (0.24)	0.17 (0.13)
Ankle internal rotation	0.43 (0.23)	0.61 (0.36)	0.41 (0.16)	0.72 (0.42)	0.66 (0.44)	0.49 (0.22)	0.55 (0.23)	0.63 (0.35)	0.59 (0.25)	0.63 (0.35)
Knee flexion	1.88 (0.28)	2.05 (0.43)	1.89 (0.48)	2.21 (0.53)	1.97 (0.38)	2.25 (0.46)	2.48 (0.47)	2.37 (0.34)	2.55 (0.42)^	2.67 (0.44)^
Knee varus	1.17 (0.55)	1.66 (0.82)	1.22 (0.32)	1.80 (0.65)	1.35 (0.76)	1.60 (0.56)	1.38 (0.58)	1.76 (0.92)	1.50 (0.58)	1.96 (0.43)
Knee internal rotation	0.27 (0.22)	0.42 (0.25)	0.32 (0.16)	0.41 (0.23)	0.36 (0.19)	0.34 (0.18)	0.36 (0.20)	0.39 (0.19)	0.34 (0.15)	0.64 (0.46)
Hip flexion	3.10 (1.07)	2.79 (1.35)	2.85 (1.02)	3.03 (1.29)	3.07 (0.83)	2.94 (0.72)	3.25 (1.02)	3.13 (0.94)	3.89 (1.71)	3.70 (1.18)
Hip adduction	1.86 (0.83)	2.11 (0.61)	2.25 (0.57)	2.40 (0.47)	2.35 (0.44)	2.45 (1.17)	2.49 (0.72)	1.93 (1.08)	2.57 (0.73)	2.75 (0.45)
Hip internal rotation	0.21 (0.16)	0.21 (0.16)	0.22 (0.13)	0.22 (0.13)	0.16 (0.06)	0.22 (0.17)	0.20 (0.06)	0.27 (0.20)	0.28 (0.24)	0.16 (0.05)
GRF (BW)										
AP	0.40 (0.09)	0.40 (0.08)	0.41 (0.07)	0.42 (0.08)	0.44 (0.07)	0.43 (0.07)	0.52 (0.09)^	0.49 (0.11)	0.54 (0.08)^	0.49 (0.09)^
ML	0.14 (0.07)	0.17 (0.06)	0.16 (0.04)	0.19 (0.06)	0.14 (0.03)	0.17 (0.07)	0.18 (0.07)	0.19 (0.07)	0.18 (0.07)	0.19 (0.08)
Vertical	3.02 (0.40)^	3.13 (0.48)^	3.09 (0.38)	3.22 (0.44)	3.16 (0.44)	3.35 (0.49)	3.52 (0.48)^	3.53 (0.50)	3.60 (0.50)^	3.62 (0.46)^

Mean (SD) values for preferred stride length and running velocity for barefoot and shod running. * Indicates significant difference between barefoot and shod conditions at a given stride length.
^ Indicates a significant difference from the respective preferred condition ($p < 0.05$).

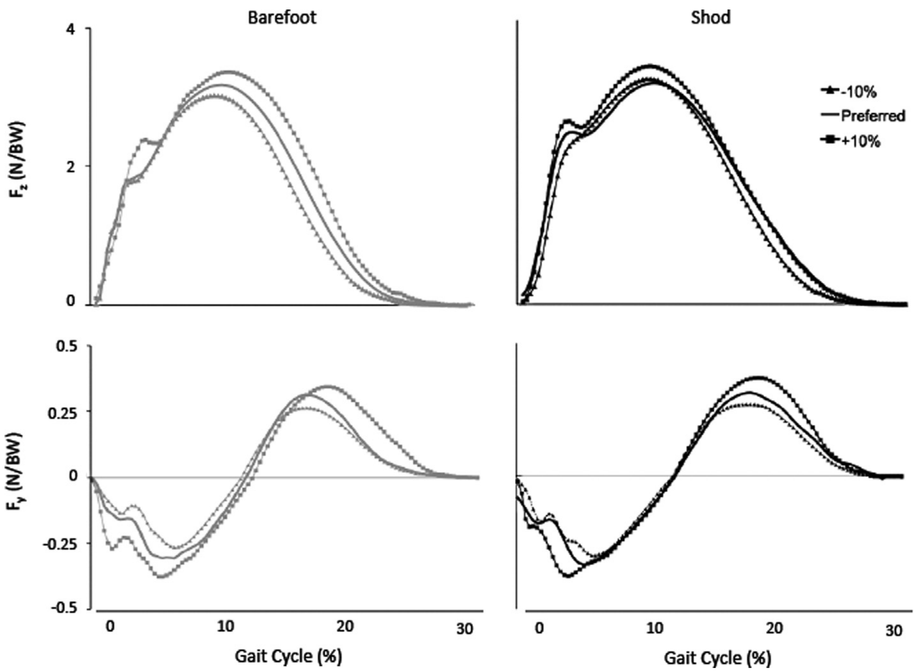

Fig. 2. Ensemble average vertical (F_Z) and anterior posterior (F_Y) GRFs for barefoot (gray) and shod (black) running at −10% (triangles), +10% (squares), and preferred (solid line) stride lengths.

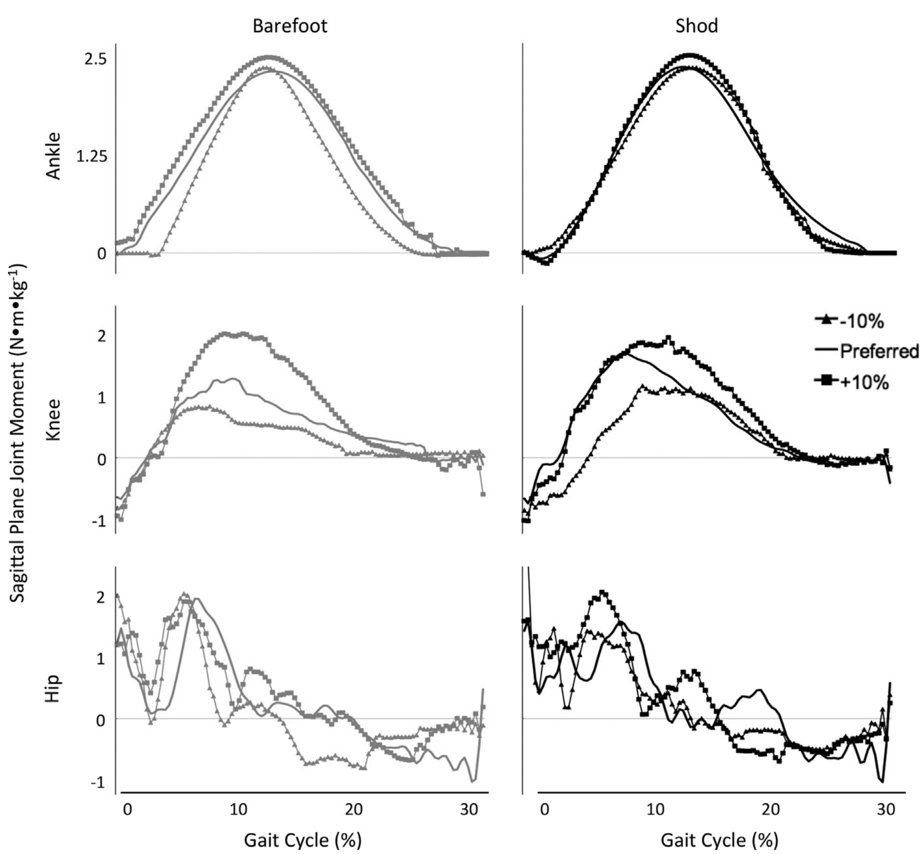

Fig. 3. Ensemble average sagittal plane joint moments at the ankle, knee, and ankle for barefoot (gray) and shod (black) running at −10% (triangles), +10% (squares), and preferred (solid line) stride lengths. *Note*: figures have different scales.

length are not reported, Braunstein et al. (2010) showed that wearing running shoes increased the moment arm of the GRF at both the ankle and knee in comparison to barefoot running.

Increased GRF magnitude is also an important factor in the greater peak sagittal plane joint moments that were observed with increased stride length. The greater GRFs are likely due to changes in center in mass (COM) trajectory, leg joint angles and lower extremity stiffness (Derrick 2004; Heiderscheit et al., 2011; Lafortune et al., 1996). Increasing stride length has been shown to increase COM excursion, COM velocity and the distance

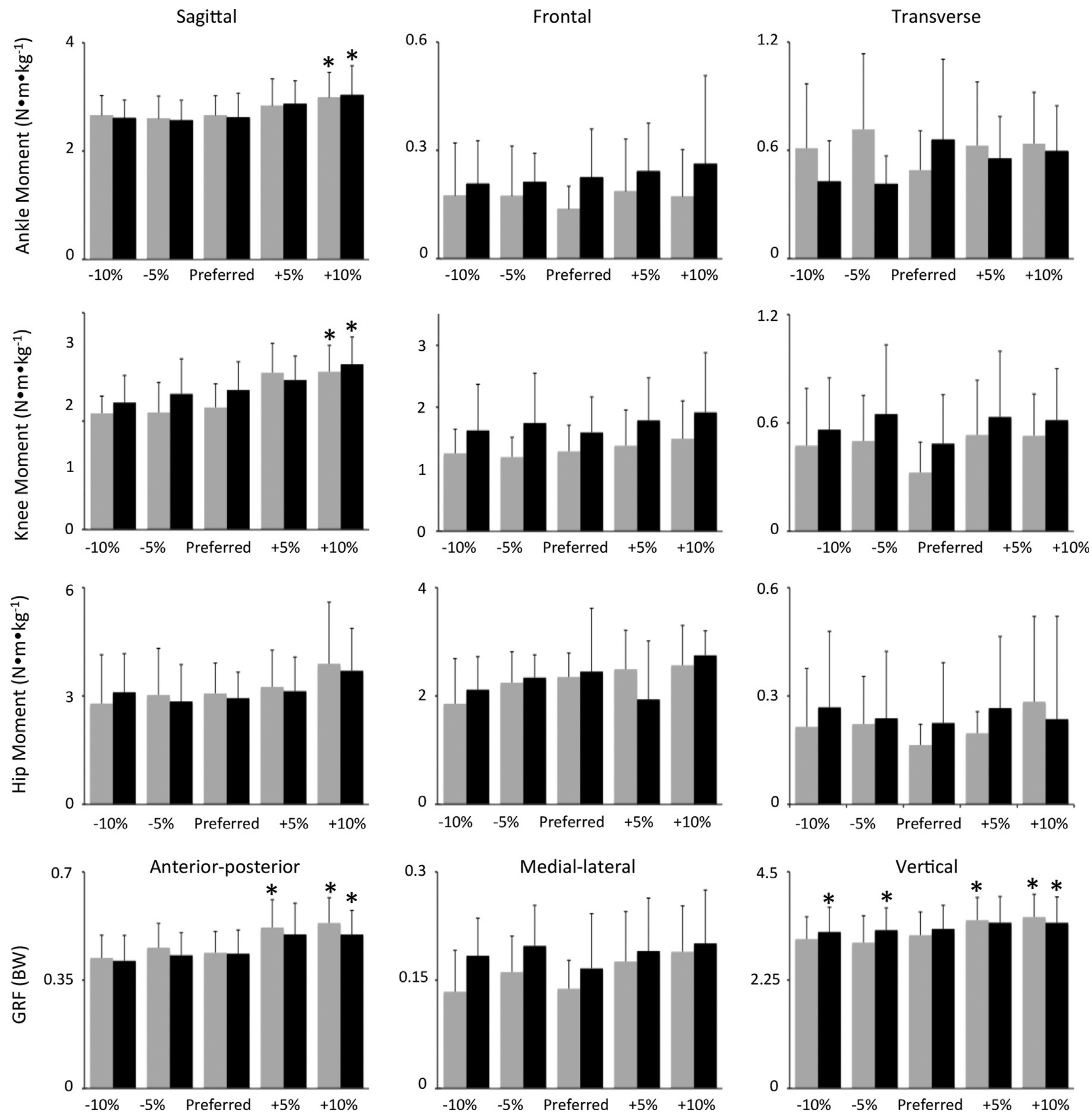

Fig. 4. Peak joint moments and GRFs ankle for barefoot (gray) and shod (black) running at in each of the stride length conditions. *Indicates significant difference from preferred condition, $p < 0.05$. *Note*: figures have different scales.

from the heel and COM at ground contact, as well as decrease leg stiffness, all of which potentially influence GRFs and joint moments (Derrick et al., 1998; Farley and Gonzalez, 1996; Heiderscheit et al., 2011). These kinematic changes are similar to those reported for comparisons of barefoot and shod running, and while not addressed in the current study, the kinematic changes associated with barefoot running may also be a factor of stride length rather than the result of wearing shoes.

Our comparison of the preferred barefoot and shod conditions is consistent with previous studies, which have shown that when running barefoot individuals adopt a shorter stride length (Altman and Davis, 2012; Jenkins and Cauthon, 2011; Nigg, 2009). Further, we have also shown that when running over-ground, on average, inexperienced barefoot runners run slower than they do in the shod condition. The majority of studies that have evaluated barefoot and shod running have utilized a motor driven treadmill (e.g. Divert et al., 2005; Kerrigan et al., 2009; Squadrone and Gallozzi, 2009), which as compared to over-ground running, have been associated with changes in temporal factors (Elliott and Blanksby, 1976; Nelson et al., 1972) kinematics (Nigg, et al., 1995; Wank et al., 1998) and kinetics (Riley et al., 2008). While treadmills create a standardized environment, running velocity is determined by the motor speed rather than being selected by the runner. Alternatively, over-ground running allows the runner to freely accelerate and decelerate, thereby allowing for more accurate analysis of a runner's preferred velocity. Velocity changes have important kinetic implications, as increased running speeds are associated with greater joint moments and GRFs (e.g., Arampatzis et al., 1999; Hamill et al., 1983). Increased running speeds have also been linked with increased injury risk (Hreljac, 2004). While we were interested in observing both running velocity and stride length changes in the preferred gait conditions, our primary goal was to examine the effect of stride length. Therefore, to avoid the complications associated with running velocity, we used a motorized pulley system to ensure that individuals ran at their preferred shod running velocity for the altered stride length conditions.

Our findings of increased GRFs and sagittal plane joint moments are comparable to the results of Derrick et al. (1998) and Heiderscheit et al. (2011) who examined the effect of stride length on shod running dynamics. Our results show a significant main effect of stride length on anterior–posterior and vertical GRFs, and sagittal plane knee and ankle moments in both barefoot and shod running. At a given stride length, we did not observe significant differences between barefoot and shod running for any of the variables tested. Further, we found no significant differences between the preferred barefoot and shod conditions, despite an average difference in stride length of 8.5%. It is possible that no significant differences were observed between the preferred conditions because there was considerable individual variation in the magnitude of stride length and velocity changes (stride length range = 1–17%, velocity range = 0–9%). While we found no significant differences between preferred barefoot and shod conditions, previous studies have reported significant differences in joint moments and GRFs between barefoot and shod running (Bonacci et al., 2013; Kerrigan et al., 2009). These studies also report differences in frontal and transverse plane moments between barefoot and shod running, whereas in the present study we only found stride length effects in the sagittal plane. However, there is little consensus in the literature as to the specific differences in GRFs and joint moments between barefoot and shod running (Bonacci et al., 2013; Kerrigan et al., 2009). For example, Kerrigan et al. (2009) found significantly greater frontal and transverse plane hip joint moments in shod running, whereas Bonacci et al. (2013) did not find significant differences in hip joint moments between barefoot and shod running. It is possible that the inconsistencies are due to methodological differences, such as over-ground versus treadmill running, the use of standardized running shoes, and/or the inverse dynamics model that was used in analysis. Further, the experience level of subjects that were tested and inherent variability between subjects could also lead to inconsistencies. Based on our results, we are confident that stride length, and not footwear, lead to the kinetic changes that were shown in the present study.

The results presented here suggest that decreasing stride length, whether barefoot or shod, produces kinetic changes that may be beneficial for prevention of running related injuries. High vertical GRFs and increased joint moments have been associated with greater risk of running related injuries (Edwards et al., 2009; Scott and Winter, 1990; van Gent et al., 2007). Our results show that decreases in stride length can reduce both vertical GRFs and joint moments. The findings of Edwards et al. (2009) support this conclusion, as they report that a 10% reduction in stride length decreases the risk of stress fracture. It is important to note that if individuals are to maintain the same running velocity while decreasing stride length there would have to be a corresponding increase in stride frequency, which could also potentially increase injury risk. However, Edwards et al. (2009) report that strain magnitude plays a more important role in stress fracture development than the total number of loading cycles. Future prospective studies should be aimed at determining if decreasing stride length can prevent running injuries.

The results presented here suggest that barefoot running itself may not lead to kinetic changes that could potentially reduce running related injuries. Rather, barefoot running triggers a decrease in stride length, which could lead to a decrease in GRFs and sagittal plane joint moments. Our results suggest that many of the biomechanical benefits attributed to barefoot running may potentially be achieved by shortening stride length, even while wearing shoes. When evaluating barefoot running as a potential option to reduce injury, it is important to consider the associated change in stride length.

Conflict of interest statement

There are no conflicts of interest associated with this manuscript.

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