

Acute changes in kinematic and muscle activity patterns in habitually shod rearfoot strikers while running barefoot

Janina Strauts¹, Natalie Vanicek^{1,2} and Mark Halaki¹

¹ Discipline of Exercise and Sport Science, Faculty of Health Sciences, University of Sydney, Australia

² Department of Sport, Health & Exercise Science, University of Hull, United Kingdom

Corresponding author:

Dr Natalie Vanicek
Department of Sport, Health and Exercise Science
University of Hull
Cottingham Rd
Hull HU6 7RX
United Kingdom
E-mail: N.Vanicek@hull.ac.uk
Fax: +44 1482 463855

Word Count: ~4,900 including all in-text references

ABSTRACT

The aim of this study was to observe changes in the kinematic and muscle activity when barefoot running was initially adopted by six habitually shod, recreational rearfoot striking runners. Participants ran on a treadmill shod for five minutes, completed 3x10-minute intervals of barefoot running then completed a final minute of shod running at self-selected pace. Dependent variables (speed, joint angles at foot-contact, joint range of motion (ROM), mean and peak EMG activity) were compared across conditions using repeated measures ANOVAs. Anterior pelvic tilt and hip flexion significantly decreased during barefoot conditions at foot contact. The ROM for the trunk, pelvis, knee and ankle angles decreased during the barefoot conditions. Mean EMG activity was reduced for biceps femoris, gastrocnemius lateralis and tibialis anterior during barefoot running. The peak activity across the running cycle decreased in biceps femoris, vastus medialis, gastrocnemius medialis, and tibialis anterior during barefoot running. During barefoot running, tibialis anterior activity significantly decreased during the pre-activation and initial contact phases; gastrocnemius lateralis and medialis activity significantly decreased during the push-off phase. Barefoot running caused immediate biomechanical and neuromuscular adaptations at the hip and pelvis which persisted when the runners donned their shoes, indicating that some learning had occurred during an initial short bout of barefoot running.

Keywords: *barefoot; running; kinematics; EMG; gait*

INTRODUCTION

Barefoot running may be considered an innate form of locomotion, dating as far back as when hunter gatherers roamed the land in search of food. An increase in recreational running prompted the development of the traditional running shoe in the 1970s. The design of the traditional running shoe, with an elevated and cushioned heel that orients the foot into a more dorsiflexed position at contact (Lieberman et al., 2010), facilitates a comfortable rearfoot strike pattern. Previous reports have confirmed that habitually shod runners tend to rearfoot strike, whilst habitually barefoot runners generally display a forefoot or midfoot strike pattern (Ahn, Brayton, Bhatia, & Martin, 2014; Altman & Davis, 2012; Divert, Mornieux, Baur, Mayer, & Belli, 2005; Lieberman, et al., 2010). However, foot strike pattern may also be speed dependent (Hatala, Dingwall, Wunderlich, & Richmond, 2013).

Running in a traditional running shoe causes runners to reduce their cadence, lengthen their stride and increase contact time, when compared to barefoot running (De Wit, De Clercq, & Aerts, 2000). Studies report increased knee flexion angles at touchdown during barefoot running (De Wit, et al., 2000) and in forefoot strikers (Lieberman, et al., 2010). A recent study also cited differences in muscle activity patterns according to foot strike pattern, such that forefoot strikers exhibited significantly earlier and prolonged plantarflexor activity prior to touchdown when compared with rearfoot strikes (van Gent et al., 2007).

The recent literature on barefoot running may encourage runners, who normally wear traditional running shoes, to consider trying barefoot running. One study has suggested that barefoot running will cause mechanical changes at the knee and ankle even in highly trained shod runners (Bonacci et al., 2013) and so runners are advised to take caution when trying barefoot running (Murphy, Curry, & Matzkin, 2013). Whilst interest in this topic has prompted researchers to explore the biomechanics of barefoot running, to our knowledge no previous work has specifically investigated the acute effects of barefoot running on joint kinematics and muscle activation patterns nor the

immediate implications barefoot running has on the body's response in individuals who have had no previous exposure to barefoot running. Understanding the immediate response to barefoot running may be of particular interest to recreational runners exploring different training programmes and to running coaches who emphasise barefoot running. Thus the aim of this study was to quantify any observed changes in the kinematic and muscle activation patterns when barefoot running was adopted by habitually shod, recreational rearfoot striking runners. This was done by exploring the immediate adaptations and also by tracking these changes at regular intervals over a 30-minute training period. A secondary aim was to ascertain whether any kinematic and muscle activation changes that occurred during the barefoot running episode were retained when participants returned to running in a shod condition. An after-effect would indicate that some learning had occurred during the 30-minute bout, which would be of interest to recreational runners who wish to engage with barefoot running programmes. We hypothesised that a 30-minute barefoot running session would cause habitually rearfoot strikers to transition to a mid- or forefoot strike pattern but that these changes would not persist once shod because the design of the traditional running shoe facilitates rearfoot striking.

METHODS

Participants

Six recreational distance shod runners (4 male and 2 female; right leg dominant; mean (SD) age: 31.5 (9.9) years; height 181.1 (11.1) cm; mass 74.5 (8.6) kg; 3-4 weekly training sessions distance per training session 10.4 (6.9) km) with a natural rearfoot strike pattern and with no extensive barefoot running experience (i.e., participants had not gone for a run barefoot previously) participated in this study. Leg dominance was determined by asking participants to mimic the action of kicking a soccer ball and subsequently to respond to a perturbation (i.e., a light push from behind). The foot which responded first was deemed as the dominant side (Schneiders et al., 2010). Rearfoot strike pattern was confirmed by the presence of an impact transient when participants ran habitually shod across a

force platform (Kistler Model 9287, Kistler Instruments Corp., AG Winterthur, Switzerland - sample rate 1500 Hz). Participants were excluded if they had no previous experience of treadmill running; had a musculoskeletal injury within the last three months; or had a known cardiovascular or neurological condition. The University of Sydney Human Research Ethics Committee approved the study and written informed consent was gained prior to testing.

Experimental Set-up

Running kinematics were captured at 100 Hz using a 14-camera motion analysis system (Motion Analysis Corp., California, USA). Electromyography (EMG) was recorded using an 8-channel telemetry EMG system (Telemetry 2400T G2, Noraxon, USA) with an amplifier gain of 1000, high-pass cut-off frequency of 10 Hz and low-pass filter cut-off at 500 Hz. The EMG signals were transmitted to a receiver (Telemetry 2400R G2, Noraxon, USA) and sampled at 1500 Hz via a 64-channel 12-bit analogue to digital board (NI PCI 6071E, National Instruments Corp., USA) synchronised to the kinematic data using Cortex 3 software (Motion Analysis Corp., California, USA).

Skin Preparation

Pairs of EMG electrodes (3 cm diameter, Kendall™ 31118733, Covidien™, Canada) were applied over eight muscles of the dominant leg: soleus, tibialis anterior, gastrocnemius lateralis, gastrocnemius medialis, vastus lateralis, rectus femoris, vastus medialis and biceps femoris. The location for electrode placement and skin preparation instructions were followed according to procedures described by Basmajian (1980). The skin over each site was shaved, abraded and cleaned with an isopropyl alcohol wipe prior to electrode positioning. Electrodes were placed appropriately in pairs, as described previously (Basmajian, 1980), directly adjacent to each other (approximately 3 cm apart), running parallel to the muscle fibre direction and reinforced with tape. Inter-electrode impedance was below 30 kΩ for each muscle.

Maximal Voluntary Contractions

With all electrodes in place, participants were instructed to perform maximal voluntary isometric contractions (MVCs) according to the protocol described by Rutherford et al. (2011) as well as plantarflexion and dorsiflexion in a seated position. Each maximal contraction was held for 3 seconds and repeated 3 times. The participants were allowed a self-determined rest time between contractions.

Reflective marker placement

Following the completion of the MVCs, 44 reflective biomechanical markers (14 mm) were affixed to the participant's trunk, pelvis, and legs, including four rigid clusters composed of four markers each which were affixed bilaterally to the participant's thigh and shank, according to the six degrees of freedom marker set (Buczek, Rainbow, Cooney, Walker, & Sanders, 2010; Cappozzo, Catani, Croce, & Leardini, 1995). The foot on the dominant right side was modelled according to the multi-segment Oxford foot model (Carson, Harrington, Thompson, O'Connor, & Theologis, 2001; Stebbins, Harrington, Thompson, Zavatsky, & Theologis, 2006) (Figure 1).

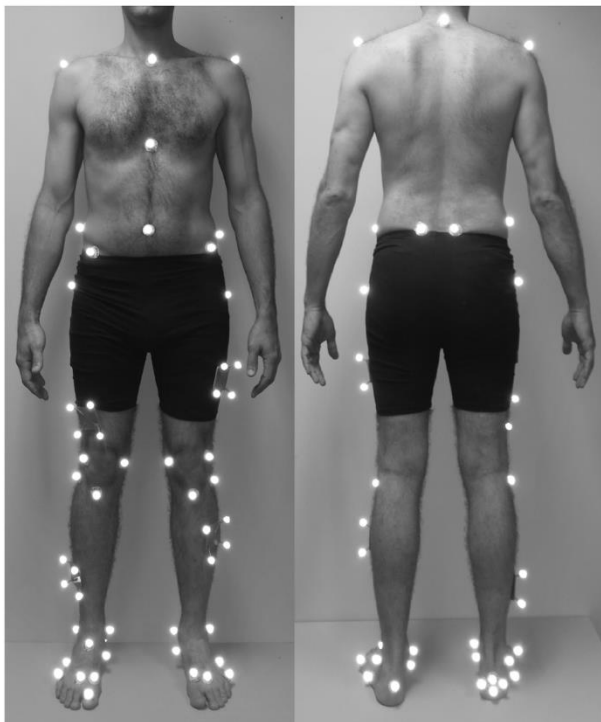


Figure 1. Reflective marker placements according to the six degrees of freedom marker set (Buczek et al., 2010; Cappozzo et al., 1995) and with an Oxford foot model (Carson, et al., 2001; Stebbins et al., 2006) on the dominant right foot only

All participants were provided with the same type of traditional running shoe for the shod condition according to their foot size (ASICS GEL-Kanbarra 5). The exact location of the markers was marked on the skin of the feet with a permanent marker, so they could be replaced with accuracy in between shod and barefoot running conditions.

Experimental procedures

Participants were instructed to run in the running shoes at a self-selected comfortable pace on a treadmill (FQTM250, Fitquip, Australia) for five minutes. Kinematic and EMG data were collected during the last minute (Shod_pre). Following this, they removed their shoes keeping the shoe markers attached. Markers were then replaced back onto the same positions on the feet.

Participants then began the 30-minute bout of barefoot running, which was divided into 3x10-minute intervals with a self-selected rest period between running intervals. They did not receive any running instructions. Participants were given approximately 30 seconds to adjust the speed (visible to the participants) of the treadmill to a comfortable speed before data collection commenced.

Participants were also given the opportunity to alter speed within the first 5 minutes of the first interval only, allowing them some time to adjust to a comfortable pace and rhythm. After the initial five minutes of the first interval, the same speed was maintained throughout the remainder of the barefoot running trials. Kinematic and EMG data were collected synchronously at every 5th minute: 1st minute (BF_1), 5th minute (BF_5), 10th minute (BF_10), 15th minute (BF_15), 20th minute (BF_20), 25th minute (BF_25) and 30th minute (BF_30).

The markers on the participant's feet were then removed; they re-donned their running shoes (with the markers still attached) and ran on the treadmill for 1 minute while kinematic and EMG data were collected (Shod_post).

Data Processing

The middle 20 seconds of each kinematic capture was visually checked and any marker switching was corrected using Cortex 3. The 20-second captures (14-18 cycles for each condition per participant) were then exported to Visual 3D (Version 4.95, C-Motion Inc., Germantown, MD, USA) where the link-model based joint angles were defined and computed. Marker position traces were interpolated using a cubic spline algorithm and low-pass filtered with a 4th order Butterworth filter with a cut-off frequency of 6 Hz. Three-dimensional joint kinematics were calculated for the trunk, pelvis, hip, knee, ankle and midfoot from the anatomical position but only the sagittal plane angles were reported. The midfoot was defined as the angle between the forefoot and the hindfoot segments. Joint kinematic and EMG data were then exported into MATLAB (Version 14, Mathworks, USA) where all EMG signals were visually checked then high-pass filtered (10 Hz, zero-lag, 8th order Butterworth), rectified, and low-pass filtered (5 Hz, zero-lag, 8th order Butterworth). The envelopes of EMG activity processed in this way were normalised to the maximum value of the processed EMG measured during the MVCs (represented as % of MVC) and resampled to 100 Hz to match the sample rate of the joint kinematics. The joint kinematic signals were filtered (5 Hz, zero-lag, 8th order Butterworth). Foot contact with the treadmill was identified as when the magnitude of the vertical velocity of any of the right hallux, inferior calcaneus or the distal 1st metatarsal were $<0.01 \text{ mm}\cdot\text{s}^{-1}$. If the inferior calcaneus marker was identified as making contact first, the foot strike pattern was categorised as a heel strike. If the hallux or distal 1st metatarsal markers were identified as making first contact, then the foot strike pattern was categorised as a forefoot strike. Toe-off was identified when the right hallux marker had a vertical velocity $\geq 0.01 \text{ mm}\cdot\text{s}^{-1}$. The stance time defined as the duration of foot treadmill contact was calculated as the difference between foot contact and toe-off for each step and normalised to total step time. The mean and peak EMG levels were calculated across steps and the mean EMG calculated during the pre-activation phase (defined as the 50 ms before foot contact), initial contact phase (defined as the first half of the foot/treadmill contact duration) and during the push-off phase (defined as the second half of the foot/treadmill contact duration) (Shih, Lin, & Shiang, 2013). The joint range of motion (ROM) was calculated during the

following phases: swing (non-contact), initial contact (first 50% of stance) and push-off (remaining 50% of stance). All signals were then time normalised to 101 points between each consecutive start of foot treadmill contact and averaged across steps.

Statistical Analysis

Dependent variables included running speed ($\text{m}\cdot\text{s}^{-1}$); stance time (% cycle); lower limb sagittal joint kinematic angles at foot contact ($^{\circ}$); ROM of lower limb sagittal joint kinematic angles during swing, initial contact and push-off phases; mean muscle activity levels (% MVC) during pre-activation, initial contact and push-off phases; and mean and peak muscle activity (% MVC) during the gait cycle according to each condition. The normality of the data was checked and confirmed using Kolmogorov-Smirnov test. Repeated measures ANOVAs (Statistica Version 10 Statsoft, USA) with one factor (condition) were performed to compare each of the EMG activation levels and kinematic variables across the different conditions. Fisher's LSD post-hoc test was used to compare the different conditions (Shod_pre, BF_1, BF_5, BF_10, BF_15, BF_20, BF_25, BF_30 and Shod_Post) when significant ANOVA results were obtained. A significance level of $\alpha=0.05$ was used. Partial eta squared (η_p^2) values are provided as a measure of effect size.

RESULTS

Running speed and stance time

Participants ran with a mean (SD) speed of 9.8 (1.9) $\text{km}\cdot\text{hr}^{-1}$ when shod (both before and after barefoot training). They started at 8.5 (1.1) $\text{km}\cdot\text{hr}^{-1}$ during the first minute of barefoot training and gradually increased during the next 4 minutes to, and continued at, 9.2 (1.4) $\text{km}\cdot\text{hr}^{-1}$ when barefoot. There was a significant difference between mean shod and barefoot running speeds ($F(5,25)=5.45$, $p<0.01$, $\eta_p^2=0.52$). However, post-hoc analysis revealed a significant difference in running speed between the first 2 minutes of barefoot running when compared to shod ($p<0.01$) but no differences

at 3 minutes or beyond ($p \geq 0.12$). Stance time was similar in the shod and barefoot conditions

($F(12,60)=0.87$, $p=0.55$, $\eta_p^2=0.15$), with a mean of 49.2 (1.2) % stride time.

Joint kinematics

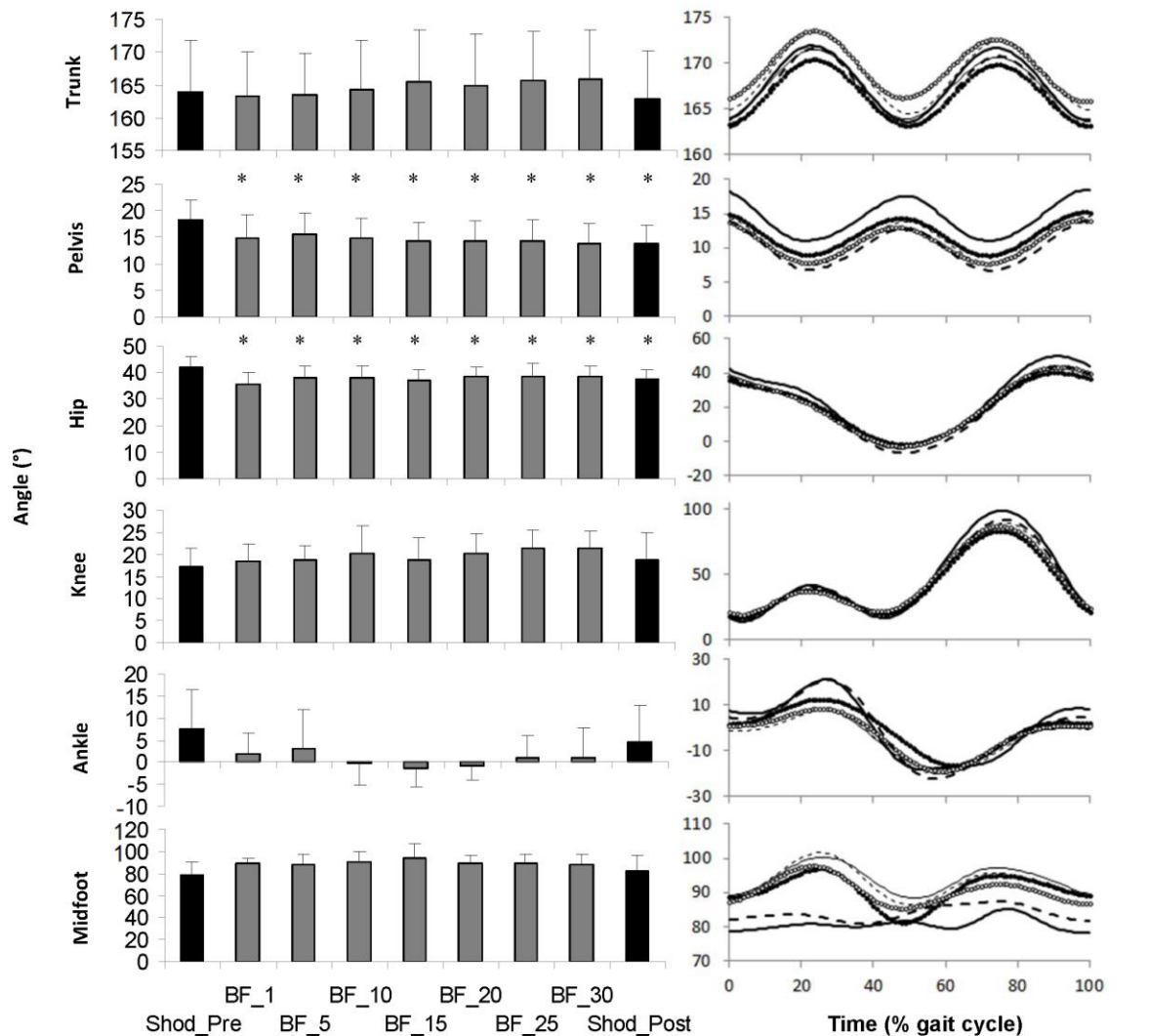


Figure 2. Sagittal joint angles at foot contact (Right leg only). Positive values indicate anterior pelvic tilt, hip and knee flexion and ankle and midfoot dorsiflexion. *=indicates significant difference when compared to Shod_pre, $p < 0.05$.

The time normalised and averaged sagittal joint angle patterns as well as the average joint angle values at foot contact are presented in Figure 2. At contact, only the pelvis ($F(8,40)=9.95$, $p < 0.05$, $\eta_p^2=0.67$) and hip ($F(8,40)=2.75$, $p < 0.05$, $\eta_p^2=0.35$) angles exhibited significant differences between shod and barefoot running conditions. The post-hoc tests revealed that anterior pelvic tilt and hip

flexion significantly decreased by $\sim 3^\circ$ and $\sim 4^\circ$, respectively, at foot contact during BF_1 ($p < 0.05$), continued through all BF conditions ($p < 0.05$) and was retained in the Shod_post condition ($p < 0.05$) compared to the Shod_pre condition. There was a trend to increased midfoot dorsiflexion ($F(8,40) = 2.09$, $p = 0.06$, $\eta_p^2 = 0.29$) by $\sim 10^\circ$ upon foot contact. No significant changes were found for the trunk, knee or ankle angles at foot contact ($F(8,40) < 1.58$, $p > 0.16$, $\eta_p^2 = 0.19-0.24$). All participants continued to adopt a rearfoot strike pattern throughout all barefoot running intervals.

Table 1 displays the mean (SD) of the sagittal joint ROM during swing, initial contact and push-off phases across trials for shod and barefoot conditions, as well as the post-hoc results identifying differences between conditions during each phase. There was a significant difference between conditions in trunk ROM during both the initial contact ($F(8,40) = 2.32$, $p < 0.05$, $\eta_p^2 = 0.32$) and the push-off phases ($F(8,40) = 5.26$, $p < 0.05$, $\eta_p^2 = 0.51$). A significant difference was also noted between conditions in pelvic ROM during the push-off phase only ($F(8,40) = 4.03$, $p < 0.05$, $\eta_p^2 = 0.45$). We found a significant difference between conditions in knee ROM during the swing ($F(8,40) = 3.38$, $p < 0.05$, $\eta_p^2 = 0.40$) and the initial contact phases ($F(8,40) = 3.81$, $p < 0.05$, $\eta_p^2 = 0.43$). There was a significant difference between conditions in ankle ROM during the initial contact ($F(8,40) = 2.32$, $p < 0.05$, $\eta_p^2 = 0.32$) and the push-off phases ($F(8,40) = 5.53$, $p < 0.05$, $\eta_p^2 = 0.52$). No significant differences between conditions were observed for any other angles or phases ($F(8,40) < 2.05$, $p > 0.07$, $\eta_p^2 = 0.13-0.29$).

EMG results

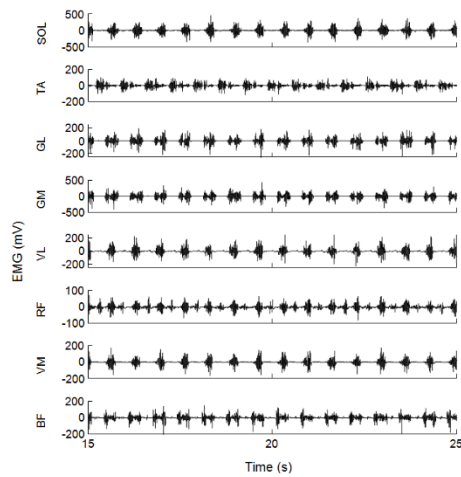


Figure 3. A 10-second sample of raw EMG for a typical subject during barefoot running BF_25 from soleus (SOL), tibialis anterior (TA), gastrocnemius lateralis (GL), gastrocnemius medialis (GM), vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM) and biceps femoris (BF)

A sample of the raw EMG for a typical participant during barefoot running BF_25 is shown in Figure 3. The mean EMG levels across the running cycle significantly decreased for soleus, tibialis anterior, gastrocnemius lateralis, vastus medialis and biceps femoris muscles in barefoot running compared to the Shod_pre condition ($F(8,40) \geq 2.19$, $p < 0.05$, $\eta_p^2 = 0.30-0.43$). As shown in Figure 4, the post-hoc test revealed that there were significant ($p < 0.05$) decreases in the average soleus activity at BF_25 and BF_30 compared to the Shod_pre condition and also at BF_25 compared to the Shod_post condition. There were also significant ($p < 0.05$) reductions in tibialis anterior activity in all barefoot training intervals, including Shod_post, but except for BF_10, compared to the Shod_pre condition. There were significant ($p < 0.05$) decreases in the average gastrocnemius lateralis activity from BF_5 to BF_30 compared to Shod_pre, and in the average vastus medialis activity in BF_15 and BF_30 ($p < 0.05$) when compared to Shod_pre as well all barefoot training intervals compared to Shod_post. Significant reductions in the average biceps femoris activity in all the barefoot training intervals in comparison to Shod_pre were also noted. No other significant differences were observed between conditions of the mean EMG levels in any of the other muscles ($F(8,40) < 1.32$, $p > 0.26$, $\eta_p^2 = 0.13-0.23$).

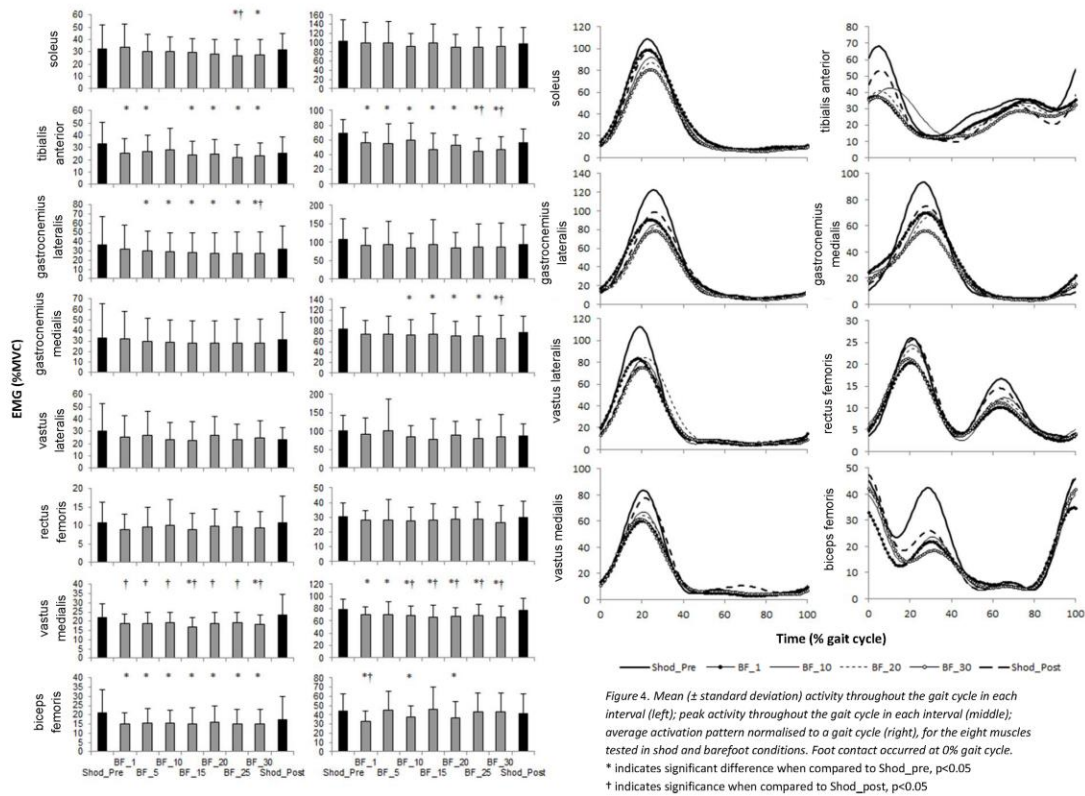


Figure 4. Mean (\pm standard deviation) activity throughout the gait cycle in each interval (left); peak activity throughout the gait cycle in each interval (middle); average activation pattern normalised to a gait cycle (right), for the eight muscles tested in shod and barefoot conditions. Foot contact occurred at 0% gait cycle. * indicates significant difference when compared to Shod_pre, $p < 0.05$. † indicates significance when compared to Shod_post, $p < 0.05$.

Table 2 provides the mean EMG levels for each of the muscles during the pre-activation, stance and push-off phases. Significant changes were found in tibialis anterior during the pre-activation and initial contact phases, and gastrocnemius medialis and lateralis, vastus medialis and biceps femoris during the push-off phase ($F(8,40) \geq 2.19$, $p < 0.05$, $\eta_p^2 = 0.30-0.43$). No other significant differences were observed between conditions at different phases in any of the other muscles ($F(8,40) < 1.82$, $p > 0.10$, $\eta_p^2 = 0.04-0.27$).

The peak EMG activity across the running cycle significantly decreased for tibialis anterior, gastrocnemius medialis, vastus medialis and biceps femoris muscles in barefoot running compared to the Shod_pre condition ($F(8,40) \leq 2.22$, $p < 0.05$, $\eta_p^2 = 0.19-0.50$). As shown in Figure 4, the post-hoc test revealed that there were significant ($p < 0.05$) decreases in the peak tibialis anterior activity during all barefoot conditions compared to the Shod_pre condition and also during BF_25 and BF_30 compared to the Shod_post condition. The Shod_post also exhibited lower peak EMG activity in tibialis anterior than the Shod_pre condition. There were significant ($p < 0.05$) declines in the peak

gastrocnemius medialis activity during the BF_10 through BF_30 conditions compared to the Shod_pre condition and also during BF_30 compared to the Shod_post condition. Significant ($p < 0.05$) decreases were also noted in the peak vastus medialis activity during all barefoot conditions compared to the Shod_pre condition and also during BF_10 through BF_30 compared to the Shod_post condition. Significant ($p < 0.05$) reductions in the peak biceps femoris activity during BF_5, BF_10, and BF_20 conditions compared to the Shod_pre condition and also during BF_1 compared to the Shod_post condition were observed. No other significant differences were detected between conditions in the peak EMG of any other muscles ($F(8,40) < 2.09$, $p > 0.06$, $\eta_p^2 = 0.12-0.29$).

DISCUSSION

The aim of our study was to measure the changes in joint kinematics and muscle activation patterns during and following a 30-minute bout of barefoot running in rearfoot strikers accustomed to running shod. Our results revealed that habitually shod runners initially ran significantly slower during the first two minutes when adapting to a barefoot running condition on a treadmill, before increasing their speed somewhat. The average self-selected barefoot running speed in our study ($9.2 \pm 1.4 \text{ km} \cdot \text{hr}^{-1}$) was similar to the speed reported in previous research by Shih et al. (2013) ($9.0 \text{ km} \cdot \text{hr}^{-1}$). We believe our study is the first to confirm that runners initially run significantly more slowly ($8.5 \pm 1.1 \text{ km} \cdot \text{hr}^{-1}$) when adapting to barefoot running. Moreover, all participants retained a rearfoot strike pattern, as evidenced by the heel making foot contact initially, during all barefoot running intervals. This may be partially explained by the relatively slow (i.e., endurance) speed adopted by our recreational runners (Hatala, et al., 2013) and/or the relatively short duration of the barefoot running bout (30 minutes).

Joint kinematics

The sagittal angles reported in the current study during the Shod_pre condition are similar to those previously reported for the trunk (Schache, Blanch, Rath, Wrigley, & Bennell, 2002), pelvis (Schache,

et al., 2002), hip (McCarthy, Fleming, Donne, & Blanksby, 2014; Shih, et al., 2013; Williams, Green, & Wurzinger, 2012), knee (Shih, et al., 2013; Williams, et al., 2012) and ankle (Shih, et al., 2013; Williams, et al., 2012) angles.

Two recent studies investigating barefoot and shod running demonstrated that kinematic and/or kinetic changes occurred between barefoot running and shod running conditions (Bonacci, et al., 2013; McCarthy, et al., 2014). In these studies, participants were allowed a familiarisation period of either 10 days (Bonacci, et al., 2013) or at least 4 minutes (McCarthy, et al., 2014) for each running condition. Whilst these studies demonstrated changes between conditions, they were unable to investigate how quickly participants adapted to the different footwear conditions. We evaluated the immediate changes in lower limb and trunk kinematics and muscle activation patterns and noted that the most significant kinematic findings occurred at the pelvis and hip with significantly less anterior pelvic tilt and less hip flexion at foot contact during every 5-minute interval over a 30-minute bout of barefoot running. Moreover, these significant findings persisted immediately when the runners re-donned their shoes. Such an after-effect suggests that some learning had occurred during the 30 minutes (Jensen, Prokop, & Dietz, 1998).

The pelvis displayed significantly less anterior pelvic tilt decreasing from $18.2 \pm 3.8^\circ$ during the Shod_pre condition, to values ranging from 13.8 - 15.7° in all barefoot training intervals immediately when barefoot running commenced. This was then further retained in the Shod_post condition with $13.8 \pm 3.5^\circ$ of anterior pelvic tilt. Visual inspection of Figure 2 indicates the ankle became less dorsiflexed at foot contact during barefoot running when compared to the Shod_pre training condition, although these differences were not significant. This suggests that kinematic adaptations occurred very quickly at proximal joints, but not at distal joints, as we might have anticipated based on existing literature that has highlighted the forefoot strike pattern associated with barefoot running (Lieberman, et al., 2010). It is possible that an initial bout of barefoot running, on a treadmill in habitually shod runners, did not expose kinematic differences at the midfoot, ankle and knee as

reported previously in the literature (De Wit, et al., 2000) because the treadmill cushions foot impacts with the treadmill belt more than a paved surface outside. Therefore, runners who initially explore barefoot running on more compliant surfaces (such as sand, grass, running tracks or a treadmill belt) may not alter their lower limb joint kinematics to the same extent as those running on hard surfaces.

To our knowledge, only three previous studies measured sagittal plane hip angles at initial foot contact (McCarthy, et al., 2014; Shih, et al., 2013; Williams, et al., 2012) and none of the studies found significant differences between shod and barefoot conditions. However, two of the studies prescribed foot strike patterns to their participants (Shih, et al., 2013; Williams, et al., 2012) and only Shih et al. (2013) noted significantly less hip flexion when forefoot striking compared to rearfoot striking. Our findings could be associated with a gradual transition to a forefoot strike pattern as evidenced by a slight but non-significant decrease in dorsiflexion ankle angle after 30 minutes of barefoot running. The changes we observed at the pelvis and hip angle could have been associated with subtle adaptations in the ankle or midfoot angles during the bout of barefoot running; these small changes may have translated to larger changes in the pelvis and hip kinematics because of the large radius (leg length) from the point of foot contact. Thus, while immediate adaptations occurred proximally, significant differences distally at the ankle may have been observed after 30 minutes. The participants did not alter their rearfoot strike pattern during the initial 30 minute of barefoot running but may have done if the barefoot running condition had been longer. Therefore, a 30-minute bout of barefoot running may not be sufficient time to naturally alter the foot strike pattern in habitual rearfoot runners. Further research investigating adaptations over a longer running bout is warranted.

EMG

Our main findings in mean EMG across the whole cycle were seen with reduced activity in the biceps femoris, tibialis anterior and gastrocnemius lateralis during barefoot running when compared to the

Shod_pre condition. When EMG was analysed according to gait cycle phases, significantly less activity was reported in the tibialis anterior during the pre-activation and stance phases, and in both gastrocnemius medialis and lateralis during the push-off phase. Although running speed was not significantly different after 5 minutes of barefoot running, it is conceivable that subtle differences in running speed between the barefoot and shod conditions may account for some of the differences in muscle activity reported. However, it is difficult to distinguish which changes may be due to running speed and which are due to musculoskeletal adaptations to barefoot running. Future studies may wish to control speed in order to understand this relationship more clearly.

The biceps femoris showed a constant and significant decrease in mean EMG activity (Figure 4) and during the push-off phase (Table 2) throughout all of the barefoot trials, and this was retained in the Shod_post when compared to the Shod_pre condition. These results were inconsistent with those reported by Shih et al. (2013) who noted increased biceps femoris activity during the stance phase of running but only between foot striking patterns in the shod condition. Given that our participants were running barefoot but without a prescribed foot strike pattern, it is possible that biceps femoris activity responds more to foot strike action rather than footwear condition (barefoot vs. shod). Findings reported by Gavilanes-Miranda et al. (2012) indicated that biceps femoris activity was decreased during the non-support phase (at approximately 90% of the jogging cycle) in a barefoot condition. Our results also indicated decreased activity when barefoot, corroborating the reports of Gavilanes-Miranda et al. (2012). However, we noted this at approximately 30% of the gait cycle, or at the start of push-off, coinciding with hip extension (Table 2).

The changes in biceps femoris (Figure 4) matched closely with the kinematic changes of the pelvis and the hip across the gait cycle (Figure 2). The pelvis and hip clearly adapted immediately with significantly reduced anterior tilt and reduced hip flexion (i.e., more hip extension), respectively, during the gait cycle in all barefoot running intervals and also in the Shod_post when compared to the Shod_pre condition. Concomitantly, the biceps femoris showed significantly reduced average

activity throughout the gait cycle during all barefoot running intervals. The biceps femoris is a hip extensor and knee flexor, and so its reduced activity could have been explained by the significantly greater hip extension, such that less extensor muscle activity was required to counteract the external flexor moment when the hip was in a more extended position during barefoot running. Moreover, other hamstring muscles, such as semitendinosus and semimembranosus, could have been responsible for the increase in hip extension we observed, although we do not have EMG data from these muscles to understand this completely. Alternatively, reduced biceps femoris activity could have been more related to function at the knee joint. Future research could explore muscle-coactivation patterns between agonist/antagonist muscles of the hip to further explain such relationships.

Tibialis anterior displayed significantly reduced average muscle activity and during the pre-activation and initial contact phases during the barefoot running intervals. The high tibialis anterior activity levels we reported during the pre-activation phase in the Shod_pre condition are supported by (von Tscherner, Goepfert, & Nigg, 2003) where participants were instructed to rearfoot strike in shod and barefoot running conditions. Those authors concluded that the physiological differences between shod vs. barefoot conditions were greater than footwear-related differences during heel-toe running and our results corroborated their findings. Shih et al. (2013) also measured pre-activation of the tibialis anterior, and reported significantly reduced muscle pre-activation and muscle activity during stance between rear- and fore-foot striking patterns in the shod and barefoot conditions. Thus, although we did not find significantly less ankle or midfoot dorsiflexion, we did find significantly reduced tibialis anterior activity suggesting our participants were not activating their ankle dorsiflexors as much during the pre-activation and initial contact phases for the barefoot conditions. This suggests they could have been making the neuromuscular adaptations for a change towards a more forefoot strike pattern during the 30-minute bout of barefoot running (Table 2, Figure 2).

We found significantly reduced mean muscle activity in the gastrocnemius lateralis during barefoot running but surprisingly not in the soleus or gastrocnemius medialis muscles. Additionally no significant differences were found between shod and barefoot running in any of the calf musculature during the pre-activation or stance phases, which was in contrast to similar literature (Divert, et al., 2005; Shih, et al., 2013). Divert et al. (2005) suggested their participants were switching from a rearfoot to a forefoot running technique and thus the pre-activation of the plantarflexor musculature would help to the lessen heel impact, thus improving the stretch-shortening cycle and potentially facilitating better storage and return of elastic energy. The discrepancy between our findings are likely related to the fact that our participants retained a rearfoot strike pattern even after 30 minutes of barefoot running. While we found gastrocnemius medialis and lateralis showed a significant decrease in muscle activity in the push-off phase, Shih et al. (2013) reported no such difference. Keeping in mind that Shih et al. (2013) instructed their participants to run specifically with either a rearfoot or a forefoot strike pattern in shod and barefoot conditions, we allowed our participants to adapt naturally over a 30-minute period to barefoot running. Thus further research into the immediate neuromuscular adaptations habitually shod runners make when running barefoot may help elucidate the different results we have reported.

Some limitations to our study must be acknowledged. Due to our small sample size, type II errors may have played a role in the non-significant changes in some angles and muscle activity levels. Additionally, without an instrumented treadmill, we were unable to explore the immediate kinetic adaptations during an initial bout of continuous barefoot running, and this information could have explained some of the internal joint moment adaptations to different running conditions. Finally, it is possible that our participants could have displayed significant adaptations more distally at the ankle, as we hypothesised and as reported in the literature, if we had allowed them to run for longer than 30 minutes. Future studies investigating similar hypotheses could extend the length and frequency of the barefoot running protocol to measure such biomechanical changes.

CONCLUSION

The findings from this study provide further evidence that when kinematic and muscle activity changes occur in response to barefoot running, they appear immediately during a bout of barefoot running in a group of habitually shod rearfoot strikers. Moreover, some of these changes persist immediately when returning to a shod running condition, indicating that some learning has occurred. Our results further suggest that the acute kinematic adaptations occur proximally about the hip and pelvis, and that this may be a result of subtle changes occurring distally at the ankle but being amplified at the hip.

ACKNOWLEDGEMENTS

The author reports no conflict of interest.

REFERENCE LIST

- Ahn, A. N., Brayton, C., Bhatia, T., & Martin, P. (2014). Muscle activity and kinematics of forefoot and rearfoot strike runners. [Article]. *Journal of Sport and Health Science*, 3(2), 102-112. doi: 10.1016/j.jshs.2014.03.007
- Altman, A. R., & Davis, I. S. (2012). Barefoot running: biomechanics and implications for running injuries. *Current Sports Medicine Reports*, 11(5), 244-250.
- Basmajian, J. V. (1980). *Electrode placement in EMG biofeedback / by John V. Basmajian and Robert Blumenstein ; with graphics by Michael Dismatsek* (R. Blumenstein, Trans.). Baltimore: Williams & Wilkins.
- Bonacci, J., Saunders, P. U., Hicks, A., Rantalainen, T., Vicenzino, B. G., & Spratford, W. (2013). Running in a minimalist and lightweight shoe is not the same as running barefoot: a biomechanical study. *British Journal of Sports Medicine*, 47(6), 387-392.
- Buczek, F. L., Rainbow, M. J., Cooney, K. M., Walker, M. R., & Sanders, J. O. (2010). Implications of using hierarchical and six degree-of-freedom models for normal gait analyses. *Gait & Posture*, 31(1), 57-63. doi: 10.1016/j.gaitpost.2009.08.245
- Cappozzo, A., Catani, F., Croce, U. D., & Leardini, A. (1995). Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clinical Biomechanics (Bristol, Avon)*, 10(4), 171-178.
- Carson, M. C., Harrington, M. E., Thompson, N., O'Connor, J. J., & Theologis, T. N. (2001). Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis. *Journal of Biomechanics*, 34(10), 1299-1307.
- De Wit, B., De Clercq, D., & Aerts, P. (2000). Biomechanical analysis of the stance phase during barefoot and shod running. [Article]. *Journal of Biomechanics*, 33(3), 269-278. doi: 10.1016/S0021-9290(99)00192-X
- Divert, C., Mornieux, G., Baur, H., Mayer, F., & Belli, A. (2005). Mechanical comparison of barefoot and shod running. *International Journal of Sports Medicine*, 26(7), 593-598. doi: 10.1055/s-2004-821327
- Gavilanes-Miranda, B., Goiriena De Gandarias, J. J., & Garcia, G. A. (2012). Comparison by EMG of running barefoot and running shod. In G. R. Naik (Ed.), *Computational Intelligence in Electromyography Analysis - A Perspective on Current Applications and Future Challenges* (pp. 65-96). Rijeka: InTech.
- Hatala, K. G., Dingwall, H. L., Wunderlich, R. E., & Richmond, B. G. (2013). Variation in Foot Strike Patterns during Running among Habitually Barefoot Populations. [Article]. *Plos One*, 8(1). doi: 10.1371/journal.pone.0052548
- Jensen, L., Prokop, T., & Dietz, V. (1998). Adaptational effects during human split-belt walking: influence of afferent input. *Experimental Brain Research*, 118(1), 126-130.
- Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A. I., D'Andrea, S., Davis, I. S., . . . Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, 463(7280), 531-535. doi: 10.1038/nature08723
- McCarthy, C., Fleming, N., Donne, B., & Blanksby, B. (2014). Barefoot Running and Hip Kinematics: Good News for the Knee? *Med Sci Sports Exerc*. doi: 10.1249/MSS.0000000000000505
- Murphy, K., Curry, E., & Matzkin, E. (2013). Barefoot Running: Does It Prevent Injuries? *Sports Medicine*, 43(11), 1131-1138. doi: 10.1007/s40279-013-0093-2
- Rutherford, D. J., Hubley-Kozey, C. L., & Stanish, W. D. (2011). Maximal voluntary isometric contraction exercises: a methodological investigation in moderate knee osteoarthritis. *Journal of Electromyography and Kinesiology*, 21(1), 154-160. doi: 10.1016/j.jelekin.2010.09.004

- Schache, A. G., Blanch, P., Rath, D., Wrigley, T., & Bennell, K. (2002). Three-dimensional angular kinematics of the lumbar spine and pelvis during running. [Research Support, Non-U.S. Gov't]. *Human movement science*, 21(2), 273-293.
- Schneiders, A. G., Sullivan, S. J., O'Malley, K. J., Clarke, S. V., Knappstein, S. A., & Taylor, L. J. (2010). A Valid and Reliable Clinical Determination of Footedness. *Physical Medicine & Rehabilitation*, 2(9), 835-841. doi: 10.1016/j.pmrj.2010.06.004
- Shih, Y., Lin, K. L., & Shiang, T. Y. (2013). Is the foot striking pattern more important than barefoot or shod conditions in running? *Gait & Posture*, 3, 490-494. doi: 10.1016/j.gaitpost.2013.01.030
- Stebbins, J., Harrington, M., Thompson, N., Zavatsky, A., & Theologis, T. (2006). Repeatability of a model for measuring multi-segment foot kinematics in children. *Gait & Posture*, 23(4), 401-410. doi: 10.1016/j.gaitpost.2005.03.002
- van Gent, R. N., Siem, D., van Middelkoop, M., van Os, A. G., Bierma-Zeinstra, S. M., & Koes, B. W. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. [Review]. *British Journal of Sports Medicine*, 41(8), 469-480; discussion 480. doi: 10.1136/bjism.2006.033548
- von Tscherner, V., Goepfert, B., & Nigg, B. M. (2003). Changes in EMG signals for the muscle tibialis anterior while running barefoot or with shoes resolved by non-linearly scaled wavelets. *Journal of Biomechanics*, 36(8), 1169-1176.
- Williams, D. S., 3rd, Green, D. H., & Wurzing, B. (2012). Changes in lower extremity movement and power absorption during forefoot striking and barefoot running. *International Journal of Sports Physical Therapy*, 7(5), 525-532.
-

1. TABLES

Table 1: Mean (SD) sagittal joint angle ranges during swing, initial contact and push-off phases across trials for shod and barefoot conditions.

Phase	Angle	Shod Pre	BF 1	BF 5	BF 10	BF 15	BF 20	BF 25	BF 30	Shod Post
Swing	Trunk	9.7 ± 3.1	8.7 ± 3.4	7.6 ± 3.1	8.5 ± 3.1	8.6 ± 3.2	9.5 ± 3.6	8.8 ± 3.6	9 ± 3.4	11.2 ± 4.3
	Pelvis	8.1 ± 2.1	7.3 ± 1.2	6.4 ± 1.2	6.8 ± 1.3	6.8 ± 1.2	7.4 ± 1.9	6.7 ± 1.8	7 ± 1.3	9.2 ± 4.5
	Hip	13.7 ± 5.9	12.5 ± 6.7	16.4 ± 3.8	16.7 ± 5.2	17.7 ± 3.7	16.3 ± 5.8	16.4 ± 3.7	17 ± 3.5	17 ± 9.2
	Knee	29.4 ± 7.5	27.1 ± 8.7	24.3 ± 5.4*†	24.6 ± 6.5*†	23.9 ± 5.1*†	26.2 ± 8.1*	24.7 ± 6.2*†	25.2 ± 6.2*†	29 ± 8
	Ankle	16 ± 3.2	16.3 ± 6	12.4 ± 2.5	13 ± 1.6	12.5 ± 2.4	12.1 ± 3.3	11.4 ± 2.3	12 ± 3	17.1 ± 7.6
	Midfoot	9.7 ± 1.8	13.1 ± 1.6	13.2 ± 1.9	13.4 ± 3.2	12.3 ± 3.3	14.2 ± 4.5	13.4 ± 3	13.6 ± 2.8	12.6 ± 8
Initial contact	Trunk	9.5 ± 2.6†	8.9 ± 3.1†	7.8 ± 2.5†	8.8 ± 2.6†	9.4 ± 2.6†	9.8 ± 3.2	9.0 ± 3.3†	8.9 ± 3.6†	11.5 ± 4
	Pelvis	6.9 ± 1.7	6.5 ± 1.8	5.8 ± 1.5	6.1 ± 1.7	6.5 ± 1.6	6.7 ± 2.1	6.2 ± 1.7	6.2 ± 2	8.4 ± 4.3
	Hip	27.2 ± 12.3	22.6 ± 10.3	24.4 ± 5.1	25.1 ± 5.4	24.7 ± 4.5	25.8 ± 6.3	26.2 ± 5.2	25.2 ± 5.1	29 ± 7
	Knee	28.1 ± 5.4	23.8 ± 5.2*†	23 ± 3.6*†	23.3 ± 4.6*†	22.8 ± 4.7*†	23.3 ± 6.3*†	24.3 ± 6.1*	23 ± 5.7*†	27.1 ± 7
	Ankle	35.1 ± 13.2	33.2 ± 9.7†	29.3 ± 5.9†	31.2 ± 4.8†	31.4 ± 5.4†	30.7 ± 7.5†	29.6 ± 6.2†	29.2 ± 7.5†	40.2 ± 11.1
	Midfoot	14.8 ± 9.4	22.1 ± 7.6	17.2 ± 4.9	17.8 ± 7.1	16.8 ± 8.6	18 ± 4.8	19.5 ± 9.1	19.2 ± 6.9	14.6 ± 10.2
Push-off	Trunk	10.4 ± 2.9	9.1 ± 2.9*	7.7 ± 2.0*†	8.8 ± 2.7*†	9.4 ± 2.6*	9.6 ± 2.8	9.3 ± 3.1*	8.8 ± 3.5*†	9.9 ± 3.1
	Pelvis	8.2 ± 2.1	7.4 ± 1.8*†	6.9 ± 1.2*†	7.4 ± 1.5*†	7.7 ± 1.6	7.7 ± 1.5*	7.9 ± 1.5	7.5 ± 1.6*†	8.1 ± 1.8
	Hip	47.7 ± 21.6	39.5 ± 17.4	45.6 ± 6.8	46.6 ± 7.3	48.7 ± 7.6	47.2 ± 6.1	49.8 ± 8.4	47.9 ± 7.4	49 ± 7.9
	Knee	75.9 ± 21.3	64.7 ± 15.9	67.5 ± 14.6	67.7 ± 13.8	72 ± 14.7	69.5 ± 11.2	73.1 ± 16	68.2 ± 15	72.1 ± 13.5
	Ankle	44.1 ± 21.1	36.9 ± 9.8	24.2 ± 6.3*†	26.4 ± 7.2*	26.8 ± 6.9*	27.1 ± 8.6*	28.6 ± 7.3*	26.4 ± 9*	32.6 ± 8.7*
	Midfoot	26.9 ± 21.9	22.1 ± 10.4	18.5 ± 1.8	18.8 ± 4.4	18.8 ± 4.9	17.4 ± 2.9	21 ± 11.6	18.5 ± 7.2	16.2 ± 3.5

Bold and *indicate significant (p<0.05) difference compared to the Shod pre; † indicate significant (p<0.05) difference compared to the Shod post.

Table 2: Mean (SD) muscle activity levels (% MVC) during pre-activation, initial contact and push off phases across trials for shod and barefoot conditions.

Phase	Muscle	Shod_Pre	BF_1	BF_5	BF_10	BF_15	BF_20	BF_25	BF_30	Shod_Post
Pre-activation	Soleus	9 ± 4	8 ± 3	10 ± 10	9 ± 9	9 ± 4	10 ± 7	8 ± 4	8 ± 6	11 ± 6
	Tibialis Anterior	53 ± 36	38 ± 25*	36 ± 20*	28 ± 13*	27 ± 17*	25 ± 13*	26 ± 15*	27 ± 14*	37 ± 21*
	Gastrocnemius lateralis	12 ± 18	12 ± 14	9 ± 4	12 ± 9	12 ± 6	10 ± 7	11 ± 9	11 ± 8	12 ± 13
	Gastrocnemius medialis	8 ± 4	20 ± 23	24 ± 16	19 ± 14	18 ± 11	19 ± 11	17 ± 11	13 ± 11	10 ± 10
	Vastus lateralis	14 ± 14	19 ± 26	8 ± 5	10 ± 8	9 ± 8	15 ± 10	8 ± 4	8 ± 6	8 ± 6
	Rectus femoris	3 ± 2	4 ± 3	3 ± 2	5 ± 6	2 ± 1	4 ± 4	3 ± 1	3 ± 2	4 ± 6
	Vastus medialis	7 ± 5	9 ± 9	6 ± 3	6 ± 3	4 ± 3	6 ± 3	4 ± 2	5 ± 2	10 ± 7
	Biceps femoris	50 ± 27	41 ± 26	38 ± 14	41 ± 21	38 ± 20	38 ± 21	38 ± 23	39 ± 24	45 ± 33
Initial contact	Soleus	51 ± 38	61 ± 64	45 ± 28	51 ± 21	49 ± 31	42 ± 28	46 ± 29	44 ± 29	44 ± 26
	Tibialis Anterior	49 ± 32	29 ± 17*	31 ± 26*	33 ± 26*	26 ± 19*†	31 ± 16*	27 ± 16*	29 ± 15*	41 ± 30
	Gastrocnemius lateralis	49 ± 46	61 ± 70	35 ± 21	49 ± 32	46 ± 34	31 ± 26	38 ± 28	36 ± 28	40 ± 33
	Gastrocnemius medialis	43 ± 49	46 ± 37	30 ± 17	38 ± 23	34 ± 15	28 ± 15	34 ± 16	27 ± 20	29 ± 20
	Vastus lateralis	72 ± 62	59 ± 57	65 ± 75	64 ± 54	55 ± 47	57 ± 37	51 ± 40	50 ± 43	45 ± 29
	Rectus femoris	14 ± 5	14 ± 5	12 ± 6	17 ± 9	16 ± 8	14 ± 6	16 ± 6	13 ± 7	16 ± 8
	Vastus medialis	49 ± 15	45 ± 24	38 ± 17	50 ± 22	44 ± 21	39 ± 18	42 ± 16	39 ± 17	39 ± 17
	Biceps femoris	30 ± 19	20 ± 9	26 ± 15	25 ± 18	23 ± 12	22 ± 12	21 ± 12	23 ± 11	30 ± 21
Push-off	Soleus	72 ± 40	58 ± 24	65 ± 53	58 ± 34	61 ± 33	60 ± 34	61 ± 39	59 ± 38	58 ± 42
	Tibialis Anterior	16 ± 13	12 ± 6	10 ± 7	18 ± 25	11 ± 9	12 ± 10	11 ± 10	11 ± 10	12 ± 9
	Gastrocnemius lateralis	89 ± 74	61 ± 41*	69 ± 78*	64 ± 61*	68 ± 70*	58 ± 54*	64 ± 59*	65 ± 57*	71 ± 58
	Gastrocnemius medialis	78 ± 57	54 ± 26*	55 ± 36*	52 ± 35*	56 ± 36*	54 ± 32*	56 ± 36*	49 ± 41*	63 ± 44
	Vastus lateralis	41 ± 20	24 ± 11	41 ± 29	30 ± 14	26 ± 13	39 ± 28	34 ± 13	33 ± 22	30 ± 16
	Rectus femoris	12 ± 6	11 ± 6	11 ± 5	12 ± 10	9 ± 5	11 ± 4	13 ± 8	12 ± 6	15 ± 12
	Vastus medialis	35 ± 19	28 ± 15†	25 ± 13†	35 ± 21	26 ± 15†	28 ± 11†	34 ± 20	32 ± 14†	45 ± 33*
	Biceps femoris	32 ± 18	15 ± 6*	22 ± 19	16 ± 14*	14 ± 10*†	12 ± 7*†	12 ± 10*†	11 ± 10*†	27 ± 33

Bold and *indicate significant (p<0.05) difference compared to the Shod_pre; † indicate significant (p<0.05) difference compared to the Shod_post.