©Journal of Sports Science and Medicine (2015) **14**, 225-232
http://www.jssm.org

Research article

Effect of Acute Alterations in Foot Strike Patterns during Running on Sagittal Plane Lower Limb Kinematics and Kinetics

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Abstract
The purpose of this study was to determine the effect of foot strike patterns and converted foot strike patterns on lower limb kinematics and kinetics at the hip, knee, and ankle during a shod condition. Subjects were videotaped with a high speed camera while running a 5km at self-selected pace on a treadmill to determine natural foot strike pattern on day one. Preferred forefoot group (PFFG, n = 10) and preferred rear foot group (PRFG, n = 11) subjects were identified through slow motion video playback (n = 21, age = 22.8±2.2 years, mass = 73.1±14.5 kg, height 1.75 ± 0.10 m). On day two, subjects performed five overground run trials in both their natural and unnatural strike patterns while motion and force data were collected. Data were collected over two days so that foot strike videos could be analyzed for group placement purposes. Several 2 (Foot Strike Pattern –forefoot strike [FFS], rearfoot strike [RFS]) x 2 (Group – PFFG, PRFG) mixed model ANOVAs ($p < 0.05$) were run on speed, active peak vertical ground reaction force (VGRF), peak early stance and mid stance sagittal ankle moments, sagittal plane hip and knee moments, ankle dorsiflexion ROM, and sagittal plane hip and knee ROM. There were no significant interactions or between group differences for any of the measured variables. Within subject effects demonstrated that the RFS condition had significantly lower (VGRF) (RFS = 2.58 ± .21 BW, FFS = 2.71 ± 0.23 BW), dorsiflexion moment (RFS = -2.6 1± 0.61 $Nm \cdot kg^{-1}$, FFS = -3.09 ± 0.32 $Nm \cdot kg^{-1}$), and dorsiflexion range of motion (RFS = 17.63 ± 3.76°, FFS = 22.10 ± 5.08°). There was also a significantly higher peak plantarflexion moment (RFS = 0.23 ± 0.11 $Nm \cdot kg^{-1}$, FFS = 0.01 ± 0.01 $Nm \cdot kg^{-1}$), peak knee moment (RFS = 2.61 ± 0.54 $Nm \cdot kg^{-1}$, FFS = 2.39 ± 0.61 $Nm \cdot kg^{-1}$), knee ROM (RFS = 31.72 ± 2.79°, FFS = 29.58 ± 2.97°), and hip ROM (RFS = 42.72 ± 4.03°, FFS = 41.38 ± 3.32°) as compared with the FFS condition. This research suggests that acute changes in foot strike patterns during shod running can create alterations in certain lower limb kinematic and kinetic measures that are not dependent on the preferred foot strike pattern of the individual. This research also challenges the contention that the impact transient spike in the vertical ground reaction force curve is only present during a rear foot strike type of running gait.

Key words: Forefoot, rearfoot, joint moments, range of motion

Introduction

Running has become an increasingly popular activity over the last several decades. As participation rates increase, so too will the total number of injury incidences if nothing is done about injury rates in runners. It has been shown that half of all runners will experience a musculoskeletal injury and subsequently will then be 50% more likely to become reinjured (Morley et al., 2010); therefore, research aimed at preventing injuries and keeping these runners healthy is warranted. Traditionally, shoe construction has been based on providing the runner with support, stability, and lower limb guidance (Hilgers et al., 2009). However, contemporary designs are more focused on individualization or custom fits and many shoe companies now have models that are designed in an attempt to induce a forefoot (FFS) or midfoot (MFS) strike pattern (Kasmer et al., 2013). Foot strike patterns encompass rearfoot (RFS), MFS, and FFS. Current estimates state that anywhere from 74.9% to 98.12% of runners utilize a RFS pattern (Bertelsen et al., 2013; Hasegawa et al., 2007; Kasmer et al., 2013; Larson et al., 2011). RFS make initial contact with the heel. MFS make initial contact with the heel and ball of the foot simultaneously. FFS make initial contact with the ball of the foot (Hasegawa, 2007). There have been many changes in shoe designs over the years. Many of these have had the goal of improving the running experience by decreasing the chances of injury. Although this is the case, the occurrence of running related injuries has not significantly declined (Hilgers et al., 2009).

Since shoe construction and application has not been shown to decrease the rate of injury in runners, research analyzing running mechanics in an attempt to assess the origin of injury is warranted. Research has examined barefoot and/or minimalist running in comparison to shod running (Divert et al., 2005a; 2005b, Giuliani et al., 2011; Lieberman et al., 2010). The purpose behind the barefoot/minimalist trend is to convert runners from a RFS pattern to a MFS or FFS pattern. The authors hypothesized that running barefoot will decrease a runner's risk of injury as this has been shown to produce lower ground reaction forces (Lieberman et al., 2010); however, this is assuming that barefoot running will force runners into a MF or FF strike pattern. Research has shown that barefoot running does not always induce this change and can contribute to injury due to local pressures being in direct contact with the heel and no cushion to absorb the pressure (Giuliani et al., 2011). Further research is necessary to determine whether barefoot running has the potential to decrease injury in different populations as the resulting impact forces have produced mixed results (Bishop et al., 2006; De Wit et al., 2000; Giuliani et al., 2011; Lieberman et al., 2010).

It has also been shown that barefoot running demands more ankle ROM, increased knee flexion levels, increased ankle plantar flexion, and decreased knee excursion compared to shod running (Bishop et al., 2006; De Wit et al., 2000; Lieberman et al., 2010; Perl et al., 2012). However, if the foot strike pattern is not altered

Received: 29 August 2014 / Accepted: 15 December 2014 / Published (online): 01 March 2015

when changing to barefoot/minimalist shoes, this can cause injury (Giuliani et al., 2011). Therefore, altering foot strike patterns during running to better coincide with individual capabilities may help in preventing injuries and this warrants further study.

Recent research has examined differences between the FFS and RFS conditions and the results vary considerably. For example, RFS has been shown in some studies to produce higher shock attenuation (Delgado et al., 2013) and longer ground contact time (Hayes and Caplan, 2012), while other studies have found higher peak impacts (Delgado et al., 2013) and increased VGRFs (Williams et al., 2000). Other changes that have been discovered with RFS include slower average race speeds compared to FFS (Hayes and Caplan, 2012), higher lumbar ROM (Delgado et al., 2013) and decreased external dorsiflexion moments (Williams et al., 2000). The presence of an impact transient during RFS has been defined as a spike in the vertical ground reaction force during the initial 50 ms of stance (Liebermann et al., 2010). It has been suggested that this impact transient only occur with a RFS running gait and it is also thought that there are important clinical implications for runners who have this spike during initial loading of the stance phase (Lieberman et al. 2010). Figure 1 shows the difference between a vertical ground reaction force curve that presents with an impact transient and one that does not.

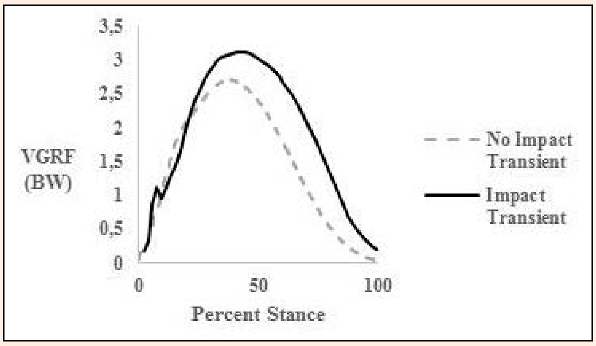

Figure 1. Sample vertical ground reaction force (VGRF) graphs showing individual trial data from one subject who does not have an impact transient and another subject who does have an impact transient.

Also, several studies have discovered kinematic and kinetic differences between different foot strike patterns, others have found no differences in overall knee ROM between RFS and FFS (Perl et al., 2012). The examination of a purposeful conversion of a RFS to a FFS and vice versa in the shod condition has been limited (Rooney and Derrick, 2013; Williams et al., 2000), and while differences were shown between converted FFS and natural FFS, there has been little reported on the conversion aspects from FFS to RFS patterns, warranting further study of the strike patterns. This may be beneficial as most runners are shod runners and changing the footwear may not be a necessary option. Runners may be able to alter their movements without changing their shoe preference. Therefore the purpose of this study was to determine the effect of foot strike patterns and converted foot strike patterns on lower limb kinematics and kinetics at the hip, knee, and ankle during a shod condition, while controlling for velocity and shoe variation.

Methods

Participants

A total of 21 subjects (10 females, 11 males, age = 22.86 ± 2.20 years, mass = 71.7 ± 14.5 kg, height = 1.75 ± 0.08 m) participated in this study. The requirements were that they had not experienced a musculoskeletal injury or had surgery within the last 6 months and were able to comfortably run a 5km in 30 minutes or less. Prior to testing, all subjects signed the informed consent approved by the University Review Board.

Instrumentation

During each participant's first visit on day 1, a Casio EX-FH100 (Casio America Inc., Dover, NJ, USA) video camera was used to record the subject's normal running gait at 120 Hz while they ran on a treadmill at their natural running pace. The camera was focused only on their feet and was used to determine each subject's natural foot strike pattern. During subsequent lab testing, kinematic data were collected using a 9 camera Qualisys (Gothenburg, Sweden) Oqus 300 motion capture system. Retro-reflective rigid body clusters were attached to the lateral aspect of the subject's right thigh and shank, as well as on top of the right foot (outside the shoe) and to the sacrum (Figure 2). Static markers were also attached to the left and right greater trochanter, left and right mid iliac crest, lateral and medial femoral condyle, lateral and medial malleolus, and 1st and 5th metatarsal. All markers were attached to the subject using tensor bandages and athletic tape. Kinematic data were collected at 240 Hz. Force plate data were collected using an AMTI (Newton, MA, USA) force platform at 2400 Hz. In order to control for running speed between trials, timing data were collected using a Tapeswitch Signal Mat (Farmingdale, NY Model CVP 1792) and a Multi-Function Timer/Counter (Lafayette, Indiana Model 54035A).

Figure 2 Subject set up with tracking markers for running trials.

Protocol

Participants came into the lab for two visits. For the first visit, the participant ran five kilometers on the treadmill at a self-selected pace. It was explained to the participant that the pace should be maintainable and continuous (as to not affect their foot strike). Music was not allowed in this trial and the participant was not provided any verbal cues. A high speed camera (Casio EX-FH100, Casio America Inc., Dover, NJ, USA) was placed lateral to the right leg and focused on the feet of the runner in the sagittal plane for all subjects. Once the treadmill trial began, five second digital footage was recorded every two minutes of the participant's foot strike. This was used to help us determine the participant's preferred foot strike pattern. After the participant had completed the initial visit, their foot strike was analyzed and they were put into one of two categories: a preferred rear foot group (PRFG) or also known as heel strikers (initial strike with rear one-third of foot), or a preferred fore foot group (PFFG), including fore foot and mid foot strikers (initial strike with middle or front one-third of foot, Delgado et al., 2013). Foot strike patterns did not change throughout the trial. A total of 10 participants were classified as PFFG and 11 participants were classified as PRFG. During the second visit, the participant was fitted to a neutral control shoe (Adidas Glide 3, Adidas AG, Herzogenaurach, Germany) of their size and they were given time to familiarize themselves with their non-preferred foot strike pattern. In order to familiarize themselves with this process, participants practiced the overground running in order to be able to successfully strike the force plate during their normal stride and at a consistent speed without altering their stride lengths or speed or sighting for the platform. Participants were allowed as much time as they needed to feel comfortable with performing their non-preferred foot strike. This was done so that when they performed the dynamic trials across the force plate, they understood the proper technique and could adequately perform it. After the participant felt comfortable with their non-preferred foot strike pattern, the retro-reflective markers were attached and the reference position trial was collected. Following the reference position trial, static markers were removed and each participant performed 5 preferred foot strike trials and 5 non-preferred foot strike trials at a comfortable pace in a random order (RFS or FFS; all RFS or FFS trials occurred simultaneously). For each trial the participant was instructed to run at their preferred pace following a straight line of 27 meters. At approximately 22 meters, the participant crossed over the force plate. For each trial the participant was instructed to start at the same point to ensure their stride allowed them to make full contact with the force plate with their right foot. Timing pads were placed before and after the force plate in order to calculate the participant's timing for each trial. The speed utilized was the self-selected speed each participant used during the five kilometer treadmill trial on day 1. This was done in an attempt to control for speed and eliminate this as a potential confounding variable for any differences found in joint kinematics/kinetics. Anterior/Posterior GRF data had been visually checked to ensure that there were not any obvious signs of speeding up/slowing down (area under the breaking and push off AP GRF curves were consistent) during the stance phase for the studied limb. Once the participant was set up, the timing mats did not move. Participants were instructed to maintain forward eye contact in order to eliminate targeting. Trials were only analyzed if the participant made full contact with the force plate at a consistent speed (all trials within a 0.1 second margin when making contact with the timing pads). The speed utilized by each subject during the overground testing on Day 2 was calculated from their treadmill speeds acquired on Day 1 by determining what time the timing mats would register for each individual runner.

Data processing

All running trials were processed using Visual 3D (C-Motion Inc., Rockville, MD, USA) software. Raw marker data were filtered using a low-pass Butterworth filter with a 12Hz cutoff frequency. The software was used to calculate the external moments and angles in the sagittal plane. Joint moments were normalized to body mass ($Nm \cdot kg^{-1}$) and calculated in the proximal coordinate system. The dependent variables included the peak external joint moments and joint ranges of motion for the ankle (early stance and mid-late stance, Figure 3), knee (Figure 4), and hip in the sagittal plane during the stance phase (from ground contact to toe off, which were defined by force platform readings as being greater than 10N and less that 10N, respectively) and the active peak vertical ground reaction force. All variables were measured in the runner's natural and unnatural foot strike pattern. Additionally, while not a dependent variable given that it did not occur in every trial, the presence or absence of an impact transient was recorded (Table 1).

Table 1. Impact transient occurrences by group (PRFG and PFFG) and condition (RFS and FFS).

	PRFG	PFFG
RFS	11	10
FFS	0	3

Note: Number in table represents the number of subjects who had an impact transient peak in their vertical ground reaction force curve. PRFG = Preferred Rear Foot Strike Group, PFFG = Preferred Fore Foot Strike Group. RFS = subjects performing a rear foot strike, FFS = subjects performing a fore foot strike.

Statistical Analysis

Mixed model 2 (Foot strike pattern – rear foot & fore foot) x 2 (group – PRFS & PFFS) repeated measures ANOVA were run using IBM SPSS Statistics 20 (IBM Corporation, Armonk, NY, USA) on the following dependent variables during the stance phase: active peak VGRF, early stance (0-20%) peak sagittal ankle moment, mid-late stance (20-100%) peak sagittal ankle moment, dorsiflexion ROM, peak knee flexion moment, sagittal knee ROM, absorption sagittal knee ROM, pushoff sagittal knee ROM, peak hip flexion moment, sagittal hip ROM. The statistical significance was set at $p < 0.05$.

Results

There were no significant interactions or main effects for between subjects factors (PRFG vs. PFFG). However, there were significant within subject main effects (RFS vs. FFS) found for eight of the ten variables tested.

Table 2. Kinematic and kinetic results for FFS and RFS trials performed by both Preferred Forefoot Group (PFFG) and Preferred Rearfoot Group (PRFG). Data are means (±SD).

	Performing FFS			Performing RFS		
	PFFG (n = 10)	PRFG (n = 11)	Total FFS (n = 21)	PFFG (n = 10)	PRFG (n = 11)	Total RFS (n = 21)
Velocity (m·s^{-1})	3.39 (.47)	3.29 (.44)	3.34 (.44)	3.28 (.39)	3.26 (.42)	3.27 (.40)
Peak VGRF (BW) †	2.76 (.24)	2.67 (.23)	2.71 (.23)	2.59 (.22)	2.56 (.21)	2.58 (.21)
Early-stance (0-20%) Ankle Mom (Nm·kg^{-1}) †	.01 (.01)	.01 (.01)	.01 (.01)	.21 (.11)	.26 (.11)	.23 (.11)
Mid-late Stance Ankle Mom (Nm·kg^{-1}) †	-3.01 (.31)	-3.18 (.32)	-3.09 (.32)	-2.53 (.30)	-2.68 (.31)	-2.61 (.31)
Dorsiflexion ROM (°) †	20.9 (5.5)	23.2 (4.7)	22.1 (5.1)	16.9 (3.1)	18.3 (4.3)	17.6 (3.8)
Peak Knee Mom (Nm/kg) †	2.41 (.75)	2.38 (.49)	2.39 (.61)	2.57 (.66)	2.64 (.44)	2.61 (.54)
Knee ROM (°)†	28.9 (3.1)	30.1 (2.9)	29.6 (3.0)	31.0 (3.2)	32.3 (2.4)	31.7 (2.8)
Knee ROM—Absorption (°)†	25.8 (2.9)	28.1 (4.6)	27.1 (4.0)	28.9 (3.3)	31.5 (2.2)	30.3 (3.0)
Knee ROM—Pushoff (°)	27.0 (4.6)	28.4 (3.1)	27.8 (3.8)	27.6 (4.8)	29.2 (3.5)	28.5 (4.1)
Peak Hip Mom (Nm·kg^{-1})	-2.19 (.72)	-2.15 (.41)	-2.17 (.56)	-2.08 (.49)	-2.27 (.40)	-2.18 (.44)
Hip ROM (°) †	40.0 (3.5)	42.6 (2.7)	41.4 (3.3)	40.9 (3.7)	44.4 (3.7)	42.7 (4.0)

Mom: Moment. † Significant main effect ($p < 0.05$) for within subjects comparing FFS to RFS conditions. All moments are calculated as external moments. At the ankle joint, positive moments are external dorsiflexion moments. At the knee joint, positive moments are external flexion moments. At the hip joint, negative moments are external flexion moments. No significant interactions, therefore there were no between subjects effects (FFG vs. RFG).

These include peak VGRF, early stance (0-20%) peak ankle moment, mid-late stance (20-100% peak ankle moment, dorsiflexion ROM, peak knee moment, knee ROM, knee ROM during absorption, and hip ROM (Table 2). The knee ROM during pushoff and the peak hip moment did not show any significant main effects.

The differences were evident on a joint by joint basis. First, the FFS condition displayed significantly higher dorsiflexion ROM and mid-late stance peak ankle moments (which were all external dorsiflexion moments, Table 2). The early stance peak ankle moment (which was predominantly an external plantarflexor moment) was significantly higher in the RFS condition (Table 2). At the knee joint, flexion moments were of greatest magnitude in the RFS condition. Additionally, the total knee ROM and the knee ROM during the absorption phase were significantly higher in the RFS condition. Hip ROM was also significantly higher in the RFS condition (Table 2).

The results also demonstrate a significant difference in peak VGRF between performing a FFS and a RFS. Peak VGRF was greater in the FFS condition. The RFS condition produced an impact transient, defined as an initial spike in the VGRF curve as a result of foot to ground contact occurring during the first 50 ms during the stance phase of running (Lieberman et al., 2010) while the FFS condition did not (Table 1).

Since velocities were controlled during data collections, not surprisingly, there were no significant differences between velocities for all groups and conditions (Table 2).

Discussion

Prior research has examined predominantly foot strike patterns in barefoot compared to shod runners or looked at the runners' natural foot strike patterns (Divert et al., 2005b; Lieberman et al., 2010) but there has been little research examining foot strike pattern conversions while controlling for footwear. One study examined RFG converted to FFG and how their new kinematics and kinetics related to a natural FFG (Williams et al., 2000) as well as joint contact loading in the two groups and two strike patterns (Rooney and Derrick, 2013). This research proves to be important as foot strike patterns continue to be a topic of debate. Some research has shown that habitually RFS runners have repetitive stress injuries at a rate

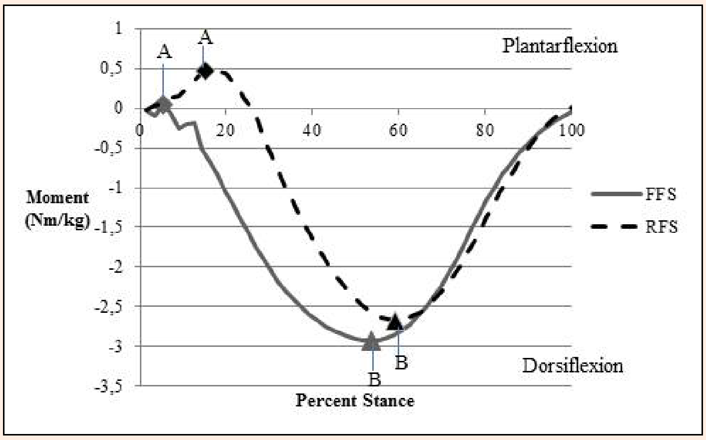

Figure 3 **Sample graphs from a single subject of the sagittal plane ankle moments for forefoot strike (FFS) and rearfoot strike (RFS) illustrating location of early-stance (0-20%) peak ankle moments (A) and mid-late stance (20-100%) peak ankle moments (B).**

2.5 times higher than habitually FFS (Daoud et al., 2012). Certain kinematic and kinetic alterations can contribute to repetitive stress injuries. It has been suggested that even though the body can adapt to stress placed upon it, repeated stress beyond the limits for each individual tissue can put an athlete at risk for an overuse injury (Hreljac and Ferber, 2006).

There were significant kinematic and kinetic differences in eight different variables between FFS and RFS conditions for both groups of runners in this study (Table 2). The ROM for the ankle, knee, and hip were significantly different between conditions: the ankle had a significantly higher ROM during the FFS trials while the knee and hip were significantly greater during the RFS trials. The ankle has been shown to play a significant role in the kinematic changes at the knee and hip during landing (De Wit et al., 2000). When a runner performs a FFS pattern, the ankle comes into ground contact plantarflexed and typically landing occurs more directly under the center of mass (Bishop et al., 2006; De Wit et al., 2000; Lieberman et al., 2010). The increased ankle ROM leads to decreased knee and hip flexion levels, thought to be in an effort to minimize the vertical movement of the center of mass (Williams et al., 2000). The results of this study demonstrate that performing a RFS lowers the ankle ROM and increases the knee and hip ROM, which suggests a minimizing of the vertical movement of the center of mass. The total knee ROM is statistically different between conditions, disagreeing with past research that has indicated no differences in total knee ROM between FFS and RFS conditions (Perl et al., 2012). This difference may be the result of controlling for stride frequency as Perl et al. had done, which was not controlled in this study. The lack of difference in this study between natural and unnatural FFG during a FFS condition did concur with the research of Williams et al. (2000). Given these results, although they are acute, may suggest that a RFS runner converting to a FFS pattern may have low tensile limits for the tissues controlling ankle ROM, possibly putting the athlete at risk for ankle injuries in the long term scenario due to overuse (Hreljac and Ferber 2006). FFS may be beneficial for those with pathologies whose treatment may require decreased ROM in the hip and knee.

These results have possible injury implications that need to be considered by runners who are contemplating switching from RFS to FFS or vice versa. Increased dorsiflexion ROM, as is evident in the FFS condition, has been linked to reduced anterior cruciate ligament loading, which could potentially place runners in a FFS pattern at reduced risk of ACL injury (Fong et al., 2011). Additionally, if a runner wishes to convert their foot strike pattern, their own history of injury needs to be considered. As is evident from the results, ROM increases or decreases in certain joints depend on which strike pattern a runner chooses to use, regardless of which strike pattern is their natural or preferred pattern. The runner needs to be able to handle the increased ROM in the given joint in order to maintain minimal vertical movement for the center of mass (Williams et al., 2000). FFS has also shown increased joint loading at the ankle, by approximately 1.3BW (Rooney and Derrick, 2013), meaning RFG who wish to convert to FFG need to take any previous ankle pathologies into account. For example, if a runner chooses to convert from a RFS pattern to a FFS pattern, the runner may need to have increased ankle flexibility to accommodate the increased ROM required. If they do not have adequate ankle ROM, the repeated stress may lead to pathologies (Hreljac and Ferber 2006). The ROM in the ankle serves as a shock absorption mechanism and if it is lacking, transitioning from RFS to FFS could subject the runner to greater peak landing forces, less knee flexion and less hip flexion, which can lead to ACL issues (Fong et al., 2011). The instantaneous and average loading rates of these peak forces also contribute to tibial stress fractures (Clansey et al., 2012). Therefore; if a runner does not have the neuromuscular capability to control the descent of the foot during the loading in a FFS, the risk for tibial stress fractures increases.

Knee ROM during absorption and pushoff were also measured. Pushoff did not show any differences between conditions and groups; however, during the absorption phase, there was a significantly greater ROM during the RFS condition. This has been theorized to be as a result of longer stride lengths during RFS conditions which lead to decreased ankle ROM and increased knee ROM (Altman and Davis, 2012). FFS runners have been shown to have shorter stride lengths which lead to greater ankle ROM and decreased knee ROM (Heiderscheit et al., 2011). The lower knee flexion levels at landing lead to the increased ROM during absorption, which contributes to the increasing moment arm distances and subsequent differences in joint moments during the RFS condition.

Studies have shown that running when performing a FFS pattern decreases the VGRF (Lieberman et al., 2010); however, our study found the opposite as the VGRF increased in the FFS condition. This finding aligns with prior research by Williams et al. (2000) who also found increased VGRF when doing a FFS condition. However, they also found significant differences in VGRF between groups and not just conditions (Williams et al., 2000). This contradicts with our findings as there were no differences between groups in the current data set, only between conditions. This may be due to the lack of differences in knee ROM between the two groups in the research by Williams et al. (2000) while in this current study, the RFS condition produced a higher knee ROM, which may have been a mechanical compensation due to the decreased ankle dorsiflexion ROM. Some research has shown increased dorsiflexion ROM is related to decreased VGRFs (Fong et al., 2011); however this research contradicts that idea as the FFS had increased dorsiflexion ROM while also having larger VGRFs. The decreased hip and knee ROM when performing a FFS may explain this difference. The increased VGRFs in the FFS condition also may place the runners at greater risk for potential overuse injury (Hreljac and Ferber 2006). It has also been hypothesized that increases in VGRF have been linked to overuse injuries (Lieberman et al., 2010) and given these results, this points to FFS patterns being more susceptible to overuse injuries.

The RFS condition displayed an impact transient for both groups while the FF strike condition eliminated the impact transient for all but three runners (Table 1). The removal of the impact transient has been theorized to be a result of several factors such as the eccentric loading of the posterior calf musculature during a FFS (Altman and Davis 2010); and small reductions in stride length achieved during FFS (Hobara et al., 2012). Our data could not elucidate the reasons why the impact transient was not present in the majority of our FFS conditions as it is most likely a result of alteration in muscular activations and EMG data were not collected as part of this study. It has previously been suggested that simply running with a FFS pattern would remove the impact transient (Lieberman et al., 2010), yet three participants in our PFFG still had an impact transient with their FFS running trials. We do not believe this presence of the impact transient is a result of our experimental methodology as it did not occur in the abnormal foot strike pattern for these three individuals. One possible explanation for this aberrant finding may be that these three subjects had inadequate hip flexor activity during the swing phase as increased hip flexor muscle activity during the swing phase has been shown to reduce the impact transient by 35%BW. It is thought that this increased hip flexor muscle activity can decrease the downward acceleration of the foot prior to contact (Schmitz et al., 2014); however, we did not measure muscle activity in our subjects. Therefore, future research is needed to determine the characteristics of runners who display an impact transient and also determine how this spike would affect their chances of injury.

It is also interesting to note that this research found an increase in peak VGRF as a result of the FFS. This raises the question whether the impulsive impact transient or an overall increase in peak VGRFs is more harmful in creating injury. It may be possible that this increase in peak VGRFs with a FFS may offset the removal of the impact transient in some runners. However; while the impact transient with a RFS pattern has been associated with injury risk (Lieberman et al., 2010), our results question the contention that simply switching to a FFS pattern would eliminate this risk as we have shown that the impact transient may still exist in FFS running gait. Clearly, more work is needed to understand how alterations in foot strike patterns affect the loading of the lower limb during running and how this affects subsequent injury rates.

We also found that the FFS condition leads to an increase in mid-late stance peak external ankle moment (which were all external dorsiflexion moments) and this aligns with previous research (Kulmala et al., 2013; Stearne et al., 2014). The increase in external ankle dorsiflexion moments has been related to an increase in ankle joint energy absorption during the first half of the stance phase (Lieberman et al., 2010). These changes in moment values have also been shown to correlate with changes in the muscular activation of the ankle joint. As the external dorsiflexion moment increases during the FFS, runners are required to counter the moment with an internal plantarflexion moment (Kulmala et al., 2013) generated by the gastrocnemius and soleus muscles. Additionally, as the external plantarflexion moment increases during RFS, an internal dorsiflexion moment created by the tibialis anterior needs to be generated. Failure to have adequate gastrocnemius and soleus strength when changing to FFS or tibialis anterior strength when changing to a RFS could have injury implications for runners, as the internal joint moments may not successfully counter the external moments which could lead to mechanical failure. Runners wishing to convert to RFS may consider reducing step rates as this has been shown to increase soleus activity, however it is important to know that decreasing step rate has not increased gastrocnemius activity (Lenhart et al., 2014).

The results of this study displayed significant kinetic differences between the conditions at the ankle and knee joints. It was found that the RFS condition increased external early stance peak ankle moments and knee flexion moments, while external mid-late stance peak ankle moments were decreased. Shod runners have been shown to have higher ankle dorsiflexion moments in the FFS condition (Rooney and Derrick, 2013; Stearne et al., 2014; Williams et al., 2000) which this research concurs with (as all mid-late stance peak ankle moments were external dorsiflexion moments). Some explanations have stated that landing in the FFS pattern results in the shorter stride length (Altman and Davis, 2010; Diebal et al., 2012) and therefore the foot lands closer to center of mass of the body, effectively reducing the moment arm of the GRF to the hip, knee, and ankle likely reducing joint moments (Altman and Davis, 2012). This research partially supports this idea with respect to knee joint moments which were significantly lower during the FFS condition although dorsiflexion moments were significantly higher during FFS condition, which agrees with results of past research (Arendse et al., 2004; Rooney and Derrick, 2013; Stearne et al., 2014; Williams et al., 2000). The hip moments displayed variable results across subjects with no significant differences between conditions or groups. Research has had mixed results with respect to joint moments as related to injury; therefore, more work is needed to determine the optimal foot strike pattern for each individual runner.

Our study does include limitations which could be addressed with future research. First, we only investigated acute effects of altering foot strike patterns. Future research should examine the mechanical changes when subjects are given more time to adjust to the new foot strike patterns. We also did not examine the muscular activation patterns of runners to see if the musculature activation of the runners may help explain the presence or absence of the impact transient and the mechanical alterations between foot strike patterns.

Conclusion

This research suggests that acutely altering the foot strike pattern of a runner in a shod condition can alter several lower limb kinematic and kinetic measures during the stance phase. It is also interesting to note that these changes are not dependent on the preferred foot strike pattern of the individual as all differences observed were simply mechanical alterations related to acutely landing on the posterior (rear foot striking) or the anterior (fore foot striking) part of the foot. This research also questions the contention that an impact transient spike in the vertical ground reaction force curve is only present during a rear foot strike type of running gait.

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Key points

- Footstrike pattern changes should be individually considered and implemented based on individual histories/abilities
- Forefoot strike patterns increase external dorsiflexion moments
- Rearfoot strike patterns increase external knee flexion moments
- Recreational shod runners are able to mimic habitual mechanics of different foot strike patterns

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