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Differences in Muscle Activity between Natural Forefoot and Rearfoot Strikers during Running

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Abstract

Running research has focused on reducing injuries by changing running technique. One proposed method is to change from rearfoot striking (RFS) to forefoot striking (FFS) because FFS is thought to be a more natural running pattern that may reduce loading and injury risk. Muscle activity affects loading and influences running patterns; however, the differences in muscle activity between natural FFS runners and natural RFS runners are unknown. The purpose of this study was to measure muscle activity in natural FFS runners and natural RFS runners. We tested the hypotheses that tibialis anterior activity would be significantly lower while activity of the plantarflexors would be significantly greater in FFS runners, compared to RFS runners, during late swing phase and early stance phase. Gait kinematics, ground reaction forces and electromyographic patterns of ten muscles were collected from twelve natural RFS runners and ten natural FFS runners. The root mean square (RMS) of each muscle's activity was calculated during terminal swing phase and early stance phase. We found significantly lower RMS activity in the tibialis anterior in FFS runners during terminal swing phase, compared to RFS runners. In contrast, the medial and lateral gastrocnemius showed significantly greater RMS activity in terminal swing phase in FFS runners. No significant differences were found during early stance phase for the tibialis anterior or the plantarflexors. Recognizing the differences in muscle activity between FFS and RFS runners is an important step toward understanding how foot strike patterns may contribute to different types of injury.

Keywords

electromyography; motion analysis; kinematics; ground reaction force

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CONFLICT OF INTEREST STATEMENT
None of the authors had any financial or personal conflict of interest with regard to this study.

INTRODUCTION

Running is a popular activity with annual injury rates as high as 56% among long distance runners (Van Mechelen, 1992). Runners who experience overuse injuries are occasionally advised to transition from a rearfoot striking (RFS) to a forefoot striking (FFS) running pattern, because FFS is thought to reduce the chance of injury. One retrospective study found that, compared with RFS, certain types of injury rates are reduced in FFS runners (Daoud et al., 2012). More research is needed to identify and interpret the differences between foot strike patterns before recommending an optimal running style.

FFS runners and RFS runners have different vertical ground reaction profiles. RFS runners show an impact peak and a higher loading rate after foot contact, whereas FFS runners often demonstrate no initial impact peak and a lower loading rate (Cavanagh and Lafortune, 1980; Laughton and Davis, 2003; Lieberman et al., 2010). Since muscle forces are largely responsible for generating ground reaction forces during running (Hamner et al., 2010), it is likely that changes in muscle activity play a role in the differences in ground reaction forces between foot strike patterns. For example,Schmitz et al. (2014) reported that increasing hip flexor activity during RFS running can decrease the loading rate.

RFS runners have a dorsiflexed ankle during terminal swing phase (Arendse et al., 2004) and early stance phase (Lieberman et al., 2010), whereas FFS runners keep their ankles in a more neutral position during late swing phase (Arendse et al., 2004) and land with a plantarflexed ankle (Lieberman et al., 2010). These differences may be related to the larger ankle plantarflexion moments measured in FFS runners during early stance (Rooney and Derrick, 2013) and greater peak ankle plantarflexion moments and stance phase Achilles tendon forces (Kulmala et al., 2013). Additionally, FFS runners land with a more flexed knee (Arendse et al., 2004; Laughton and Davis, 2003; Lieberman et al., 2010) compared to RFS runners. Although sagittal plane kinematics can be replicated by a RFS runner running with a FFS pattern (Rooney and Derrick, 2013; Stearne et al., 2014), natural RFS runners running with a FFS pattern have longer stride lengths compared to natural FFS runners (Shih et al., 2013), a reduced peak ankle plantarflexion moment (Williams et al., 2000) and increased peak ankle external rotation moment during stance (Stearne et al., 2014). It is therefore important to identify differences between natural FFS and natural RFS runners.

Muscle forces affect foot position and limb kinematics during swing phase (Piazza and Delp, 1996; Schmitz et al., 2014); thus, it is important to understand the relationship between swing phase kinematics and muscle activity. Muscle activities during running have been examined to study the effects of speed (e.g. Gazendam and Hof, 2007) and gait modifications (e.g. Giandolini et al., 2013) on muscle activity. Muscle activities have also been recorded to evaluate muscle function during running (Bartlett et al., 2014; Modica and Kram, 2005; Novacheck, 1998), test the accuracy of running simulations (Hamner et al., 2010) and estimate muscle fiber lengths and velocities (Arnold et al., 2013). Studies have reported differences in muscle activity when RFS runners ran with both their natural RFS pattern and a FFS pattern (Olin and Gutierrez, 2013; Shih et al., 2013). Just prior to foot contact, activity of the tibialis anterior was found to be greater when RFS runners ran with their natural RFS pattern, compared to a FFS pattern. When these same runners ran with a

FFS pattern, the gastrocnemius had greater activity compared to the runners' natural RFS pattern (Shih et al., 2013). During stance phase, Olin and Gutierrez (2013) reported that RFS runners using their natural pattern had greater average and peak activity in the tibialis anterior, and greater average activity in the medial gastrocnemius when these natural RFS runners used a FFS pattern. It is unknown if the same differences in muscle activity exist between natural RFS runners and natural FFS runners because muscle activities in natural FFS runners have not yet been reported.

The goal of this study was to identify how muscle activities differ between runners with a natural RFS pattern and runners with a natural FFS pattern. Since FFS runners tend to run with a more plantarflexed ankle around the time of foot contact, we hypothesized that FFS runners would show significantly lower average muscle activity in the tibialis anterior during both the end of swing phase and early stance phase. The larger peak plantarflexion moments generated by FFS runners (Kulmala et al., 2013) led us to test the hypothesis that the soleus and gastrocnemius would have significantly higher average activity in FFS runners during late swing and early stance phases.

METHODS

Subjects

Twelve natural RFS runners (age: 27.9±5.2 years; height: 171±11 cm; weight: 63.8±11.0 kg) and ten natural FFS runners (age: 29.0±6.3 years; height: 176±6 cm; weight: 64.9±7.6 kg) participated in this study. Foot strike type was confirmed after the data collection, as described below. All runners were healthy, experienced long distance runners, who reported running a minimum of 25 km/week. Each subject gave informed consent prior to participation according to a protocol approved by the Stanford University Institutional Review Board.

Following the placement of motion capture markers and electromyography electrodes, we collected data with each subject in a static standing pose. Subjects then performed bi-lateral hip circumduction to allow for estimation of hip joint centers (Piazza et al., 2004). Subjects were then asked to warm up for a minimum of five minutes to get accustomed to running on the treadmill. Following warm up, muscle activity was collected as subjects walked at 1.25 m/s. Walking patterns were assumed to be similar among the runners regardless of their running style, and the low-pass filtered peak muscle activity averaged over 3 walking gait cycles was used to normalize muscle activity during running (see below for details). Subjects then ran for a minimum of three minutes at 4.0 m/s. All data analyzed were from the same 4–6 continuous right limb running gait cycles.

Kinematic and Kinetic Analysis

Joint kinematics were estimated from 29 retro-reflective markers placed on each subject’s lower extremities. Marker positions were tracked using a passive marker motion capture system (17 subjects – Vicon, Oxford Metrics Group, Oxford, UK; 5 subjects – Motion Analysis Corporation, Santa Rosa, CA, USA). To eliminate the need for qualitative video analysis to determine foot strike pattern, markers placed on the shoe posterior and superior

to the apex of the calcaneus (heel marker) and superior to the hallux (toe marker) were used (Figure 1). The vertical position of the heel marker was subtracted from the vertical position of the toe marker during the static standing pose to establish a baseline relationship between the markers. The vertical difference between these two markers was obtained at initial contact during running and averaged over 4–6 consecutive gait cycles. Relative to baseline, a more dorsiflexed ankle at initial contact produces a larger positive value, while a more plantarflexed ankle at initial contact produces a low positive value or negative value. Subjects were classified as a FFS runner if a value of 40 mm or less was found by subtracting the baseline difference from the difference at initial contact. A subject was considered to have a RFS running pattern if the difference was greater than 70 mm between initial contact and baseline. If the difference was between 40 and 70 mm, runners were classified as a midfoot striker and excluded from the analysis. We validated this method of classifying foot strike patterns of the runners using high-speed video recordings of six runners.

Lower extremity joint kinematics were estimated using a musculoskeletal model with 16 degrees of freedom, modified from Delp et al. (1990). The model included a pelvis with six degrees of freedom, ball-and-socket joints to represent the hips, custom joints at the knees with one degree of freedom that coupled rotations and translations (Delp et al., 1990), and revolute joints at the ankles. For each subject, we scaled the musculoskeletal model using markers placed on anatomical landmarks, taken from the static standing trial, and virtual hip joint centers, estimated from the hip circumduction trials. Hip, knee, and ankle angles for each subject were found using an inverse kinematics algorithm that minimized the difference between experimentally measured marker positions and virtual markers placed on the model (Delp et al., 2007).

Ground reaction forces and moments were collected from a split-belt force-plate instrumented treadmill (Bertec Corporation, Columbus, OH, USA). Kinematic and kinetic data were used to break up the gait cycle into terminal swing phase and early stance phase for each subject. We defined terminal swing phase to be between the times of maximum swing phase knee flexion and foot contact. The vertical ground reaction force for each subject was used to define the early stance phase to occur between the times of initial foot contact and the peak vertical ground reaction force.

Electromyography

Electromyography (EMG) patterns were recorded during the walking and running trials using surface electrodes (Delsys Inc., Boston, MA, USA). We collected data from ten major surface muscles of the lower extremity, including tibialis anterior, lateral gastrocnemius, medial gastrocnemius, soleus, rectus femoris, vastus medialis, vastus lateralis, medial hamstrings, lateral hamstrings, and gluteus medius. These muscles were chosen because they provide supportive and propulsive forces during running (Hamner et al., 2010) or are direct contributors to ankle kinematics (e.g. tibialis anterior). The raw EMG signals were processed using a band-pass filter (20–480 Hz), rectified, and then passed through a critically damped low-pass filter with a 20 Hz cutoff. The signals for each subject were then

normalized to the peak processed signal found during walking. After processing the EMG signals, we averaged across 4–6 gait cycles for each subject.

Differences in muscle activity were assessed during terminal swing phase and initial stance phase. During these phases, the root mean square (RMS) of each signal was calculated for each subject. Of the 10 muscles collected from each of the 20 subjects, we eliminated the EMG signals from our analysis from one subject's vastus medialis, one subject's vastus lateralis, and two subjects' gluteus medius due to obviously poor signal quality where we found no visible modulation of muscle activity.

Statistics

A general linear univariate model was used to identify statistically significant differences between the RMS of each muscle's activity during the late swing and early stance phases between RFS and FFS running patterns. Each muscle during each of the two phases of the gait cycle was treated as independent, and post-hoc checked for a significant correlation against the other phase of the gait cycle. If a correlation was found, the significance level was adjusted using the Bonferroni correction. A general linear univariate model was also used to test for statistically significant differences between knee and ankle angles at initial contact. All analyses were done using SPSS (SPSS, IBM, Armonk, NY, USA), and significance for all analyses, before any corrections, was set at $p<0.05$.

RESULTS

We found significant differences between natural FFS and RFS runners in muscle activity of the ankle plantarflexors and dorsiflexors during late swing phase (Figure 2). The tibialis anterior had lower RMS muscle activity during late swing phase in FFS runners compared to RFS runners ($p=0.001$; Table 1); no significant difference was detected during early stance phase ($p=0.590$; Table 2).

The medial and lateral gastrocnemius had higher muscle activity during late swing phase in FFS runners, compared to RFS runners (medial gastrocnemius: $p=0.004$; lateral gastrocnemius: $p=0.001$); no significant differences were detected during early stance phase (medial: $p=0.714$; lateral: $p=0.544$). RMS activity of the soleus was not significantly different between RFS and FFS runners during late swing phase ($p=0.395$). Early stance phase RMS activity of the soleus was lower in FFS runners, but this difference was not significant ($p=0.032$) because a correlation between late swing phase and early stance phase muscle activity tightened the significance threshold to $p<0.025$.

When considering the other muscles (Table 1), FFS runners displayed lower RMS activity of the vastus medialis ($p=0.032$) and lateral hamstrings ($p=0.028$) during late swing phase, compared to RFS runners. During early stance, there were no significant differences in RMS activity of any muscles between RFS and FFS runners (Table 2).

The natural FFS runners showed differences in kinematics and the vertical ground reaction force profile compared to RFS runners. The mean ankle angle at foot contact was 11±5 degrees of plantarflexion in the FFS runners compared to 6±4 degrees of dorsiflexion in the

RFS runners ($p<0.001$). Knee flexion angle (Figure 3) was 6 degrees greater in FFS runners at foot contact ($p=0.023$). The vertical ground reaction forces (Figure 4) for the natural FFS runners demonstrated a reduced impact peak compared to the RFS runners.

DISCUSSION

Our goal was to identify differences in muscle activity between natural RFS and natural FFS runners. Because FFS runners tend to land with greater ankle plantarflexion, we hypothesized that FFS runners would show significantly lower tibialis anterior activity than RFS runners during the terminal swing and early stance phases. In partial support of this hypothesis, FFS runners ran with less tibialis anterior activity during the terminal swing phase compared to RFS runners; however, RMS activity of the tibialis anterior was not significantly different during early stance. We also hypothesized that the plantarflexor muscles would have significantly higher activity in FFS runners compared to RFS runners during the late swing and early stance phases. Again, we only partially accept this hypothesis. Compared to RFS runners, medial and lateral gastrocnemius activities were greater in FFS runners during the terminal swing phase, but not significantly different in early stance phase. During the late swing and early stance phases, there were no significant differences in RMS activity for the soleus between FFS and RFS runners.

We compared muscle activities during the late swing and early stance phases because these occur just prior to and after foot contact, an instant with significant kinematic differences between RFS and FFS runners (Arendse et al., 2004; Laughton and Davis, 2003; Lieberman et al., 2010). In agreement with Arendse et al. (2004) and Lieberman et al. (2010), the RFS runners in our study landed with greater dorsiflexion compared to the FFS runners. We detected greater tibialis anterior activity before foot contact during RFS running (Table 1), similar to Shih et al. (2013). When natural RFS runners run with a FFS pattern, greater tibialis anterior activity during stance phase has been observed (Shih et al., 2013); in contrast, our results showed no significant difference between RMS muscle activity during the early stance phase. This discrepancy may have arisen because when running with a FFS pattern, the habitual RFS runners studied by Shih et al (2013) ran with increased stride lengths compared to when they ran with a RFS pattern. This is atypical. Natural FFS runners have similar or shorter stride lengths compared to RFS runners (Almonroeder et al., 2013; Arendse et al., 2004).

Muscle activity precedes muscle force production (Winter, 2005); therefore, we expected changes in muscle activity prior to foot contact, which we confirmed in our experiments (Figure 2). Since natural FFS runners have greater average plantarflexion moments than RFS runners in early stance (Rooney and Derrick, 2013), we also expected increased activity of the plantarflexors in FFS runners during early stance. We found increased activity of the gastrocnemius in FFS runners during late swing, but not during early stance, likely because of the delay between muscle activity and muscle force. The relationship between gastrocnemius activity and the plantarflexion moment it generates is influenced by its force-length-velocity relationship (Arnold et al., 2013). FFS runners have greater ankle plantarflexion and greater knee flexion at foot contact compared to RFS runners. Thus, the plantarflexion moment generated by gastrocnemius is affected by knee and ankle angles and

angular velocities. The complex relationship between muscle activity and its force-generating capability is likely the reason why muscle activities did not increase while joint moments increase (Kulmala et al., 2013; Rooney and Derrick, 2013).

Our FFS runners had significantly greater knee flexion angles at foot contact than our RFS runners, consistent with Arendse et al. (2004), Laughton and Davis (2003) and Lieberman et al. (2010). Nevertheless, we found no significant differences in RMS activity of rectus femoris during the late swing or early stance phases in FFS runners compared to RFS runners (Table 1). In contrast,Shih et al. (2013) reported that RFS runners had greater muscle activity in the rectus femoris during swing phase when running with a FFS running pattern. However, our natural FFS runners demonstrated less RMS activity in the lateral hamstrings during terminal swing phase, which may be due to kinematic differences at the knee (Figure 3). It is interesting that RFS runners who were asked to run with both strike type patterns showed no significant difference in lateral hamstring muscles (Shih et al., 2013). The differences between our natural FFS runners and the RFS runners running with a FFS pattern studied by Shih et al. (2013) may arise due to adaptations in muscle activities made after running habitually with a FFS pattern.

It is important to consider the limitations of our experiments. Most of the runners in our study run primarily outdoors rather than on a treadmill. Runners were given time to adapt to the treadmill, but their gait patterns may differ compared to overground running (e.g. Riley et al., 2008). However, the vertical ground reaction forces of our runners (Figure 4) were similar to those reported by Laughton and Davis (2003) and Lieberman et al. (2010) for overground runners, with the FFS runners demonstrating a reduced impact peak compared to RFS runners. We required that all subjects wear shoes, but did not control the type of footwear. It is possible that some of the differences measured may have been influenced by shoe type (e.g. Holden and Cavanagh, 1991; Squadrone and Gallozzi, 2009), although Giandolini et al. (2013) found no differences in muscle activity when comparing runners using both a typical cushioned shoe and a racing shoe. Additionally, we captured and analyzed the subjects' muscle activity while running at 4.0 m/s. Although this pace was within our subjects' range of training speeds, our results may not reflect our subjects' activity patterns at their preferred training pace or another speed. RFS runners tended to run with greater soleus activity during early stance phase ($p=0.032$), however this difference was not significant due to a correlation in soleus activity between late swing phase and early stance phase (Table 2); we may have detected a significant difference if we had studied more subjects. Finally, muscle activity during running was normalized to the peak processed EMG signal during walking and assumes that muscle activity during walking is consistent between FFS and RFS runners.

Examining muscle activity patterns can reveal fundamental differences between FFS and RFS running patterns and expose potential injury risks. With greater medial and lateral gastrocnemius activity, FFS running demands more from these muscles. This difference in muscle activity should be considered when transitioning from RFS to FFS running. In contrast, RFS running requires greater activity of the tibialis anterior and lateral hamstrings compared to FFS running. The overuse of these muscles during RFS running may lead to a different set of injuries than would be expected in FFS running. Although we cannot

establish relationships between injury mechanisms and foot strike type with the data presented here, our study identified differences in muscle activity between RFS and natural FFS running patterns and provides an important step in differentiating and defining these two running patterns.

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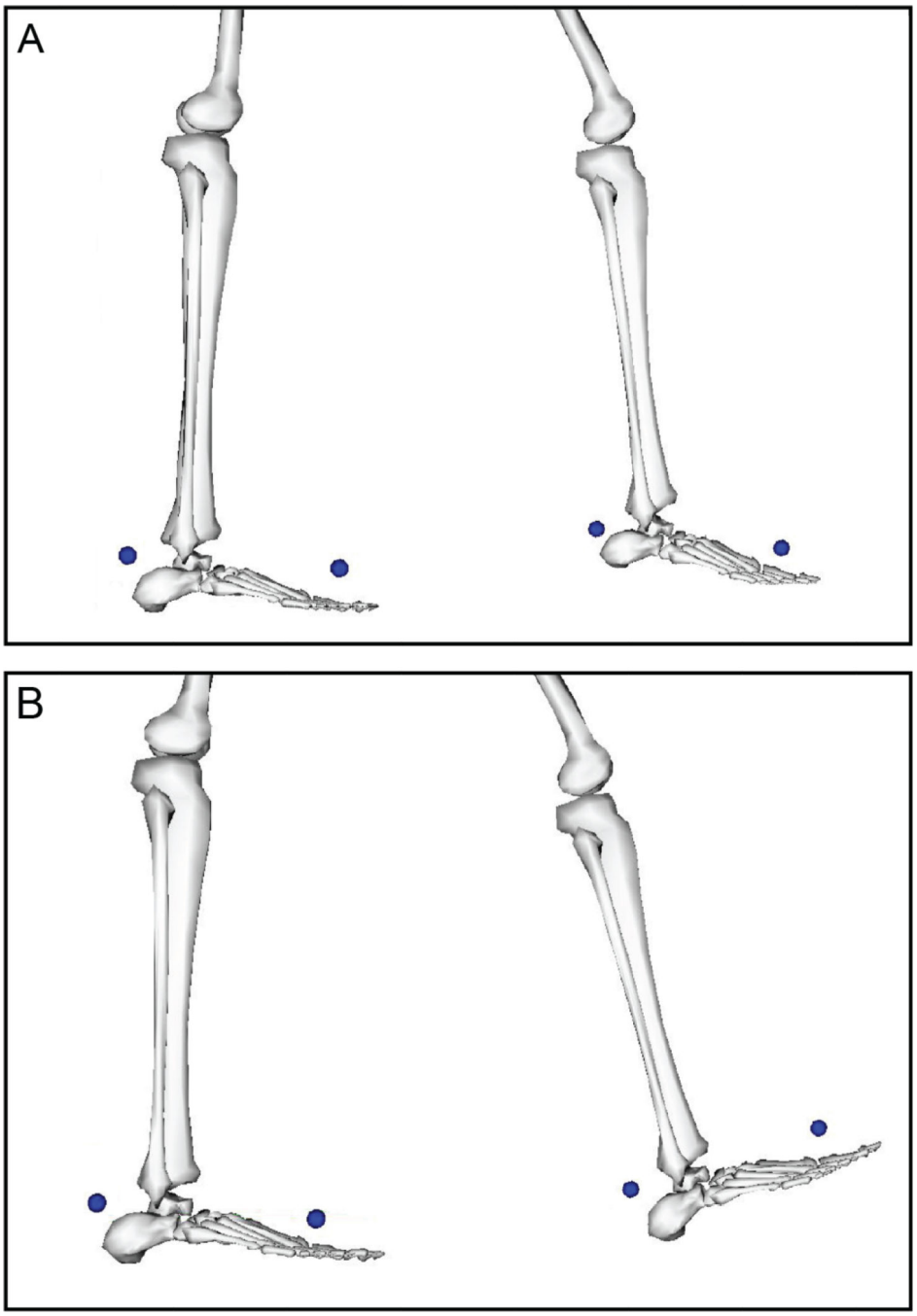

Figure 1.

(A) Segment and marker positions for a forefoot striking (FFS) runner during a standing trial (left) and at initial contact during running. (B) Segment and marker positions for a rearfoot striking (RFS) runner during a standing trial (left) and at initial contact during running. Runners were characterized as having a RFS or FFS pattern based on markers placed on the shoe, posterior and superior to the apex of the calcaneus and superior to the hallux. The differences in vertical position between the toe and heel markers were found during the

standing trial and compared to the differences at initial contact to determine the foot contact pattern.

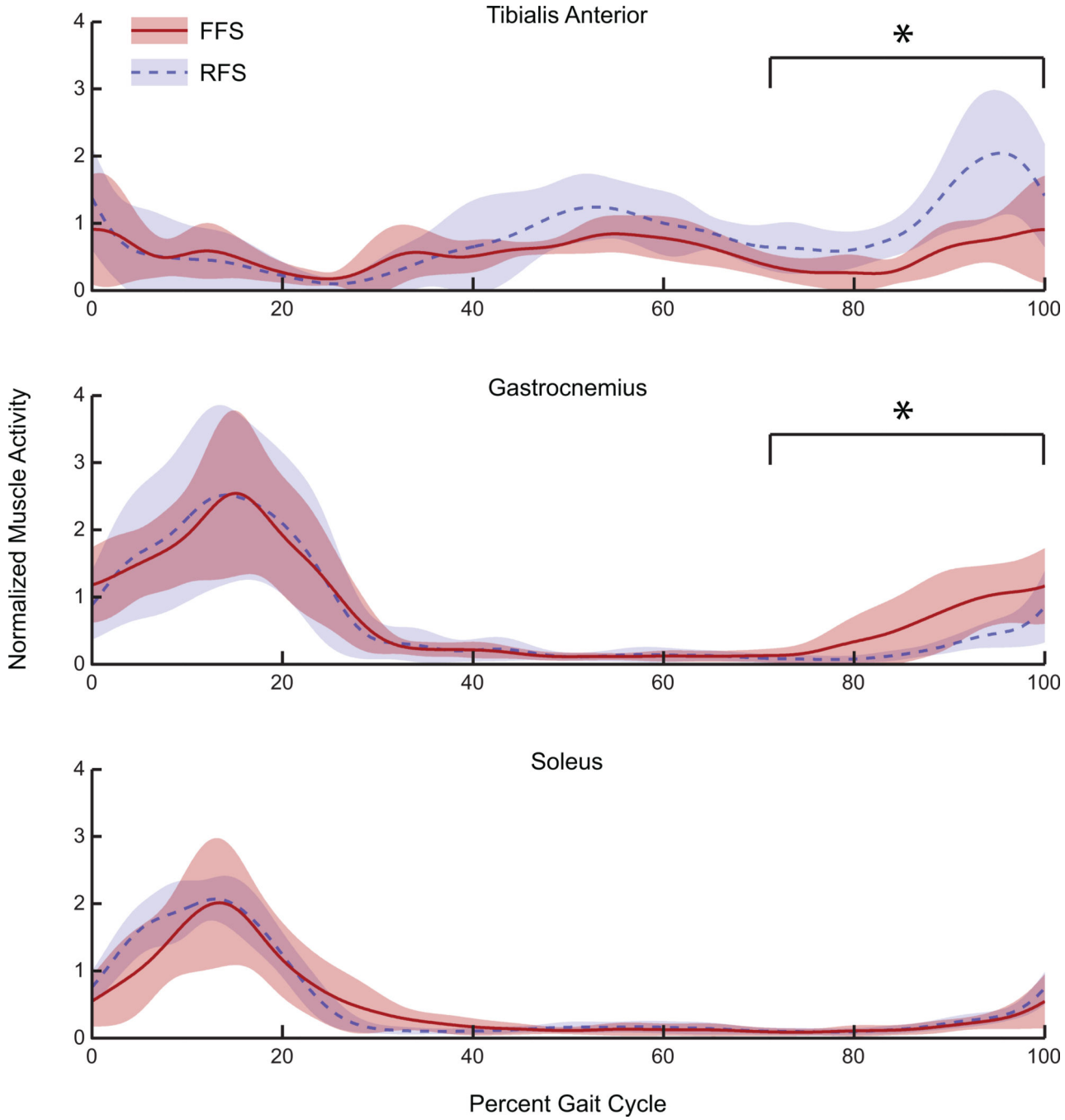

Figure 2.

Ensemble average ± one standard deviation muscle activity from the tibialis anterior, lateral gastrocnemius and soleus. Muscle activities from the forefoot striking (FFS, solid red) and rearfoot striking (RFS, dashed blue) runners were normalized to the corresponding maximum activity during walking. Activity in the tibialis anterior activity during late swing phase was significantly higher in RFS compared to FFS runners. Activity in the gastrocnemius was significantly higher in FFS runners during late swing phase compared to

RFS runners. The soleus showed no significant difference between FFS and RFS runners. * indicates significance ($p<0.05$).

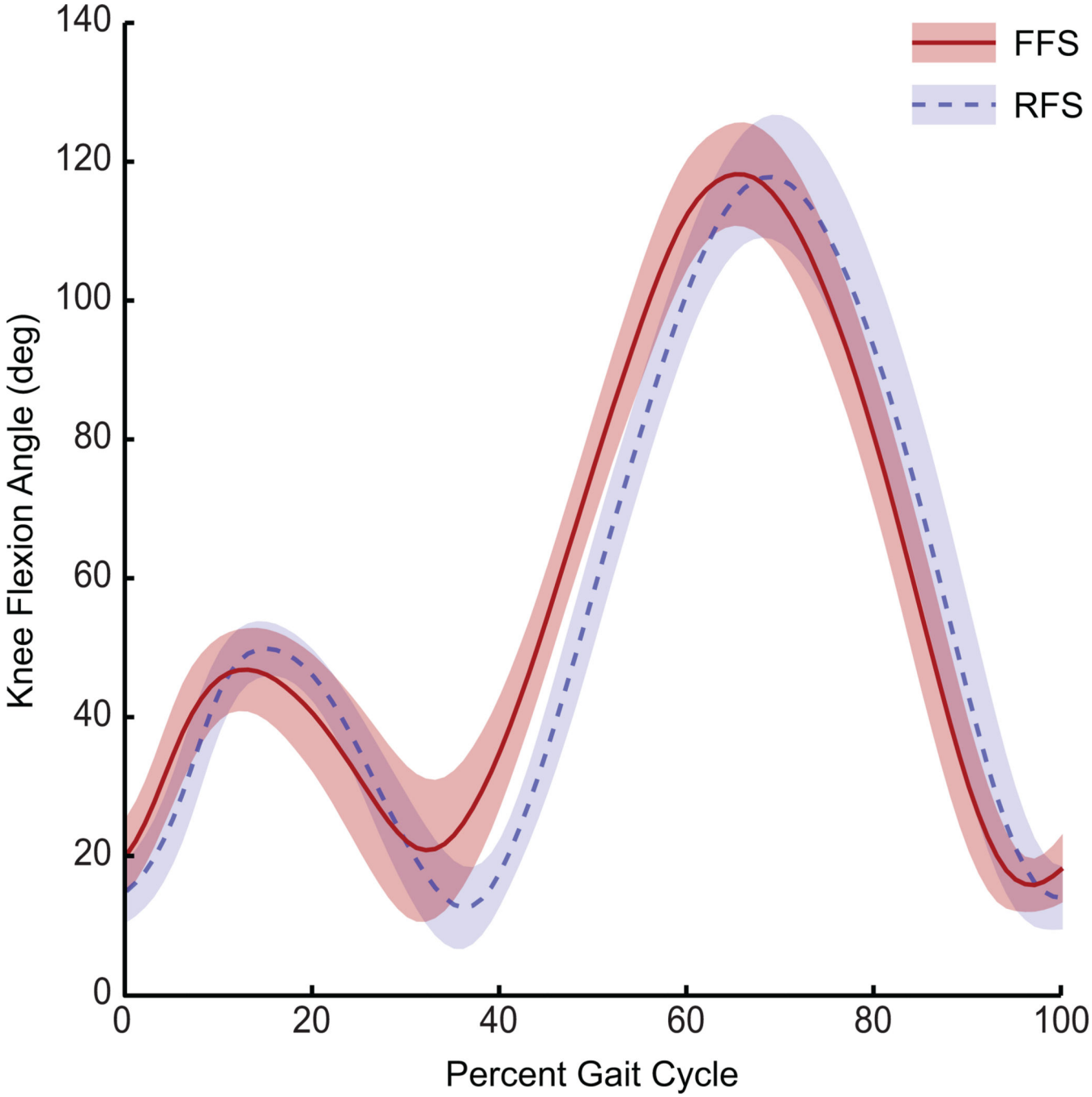

Figure 3.

Ensemble average ± one standard deviation of knee flexion angles for forefoot striking (FFS, solid red) and rearfoot striking (RFS, dashed blue) runners. The time between peak swing phase knee flexion and initial foot contact was classified as late swing phase. The FFS subjects demonstrated a more flexed knee at initial contact.

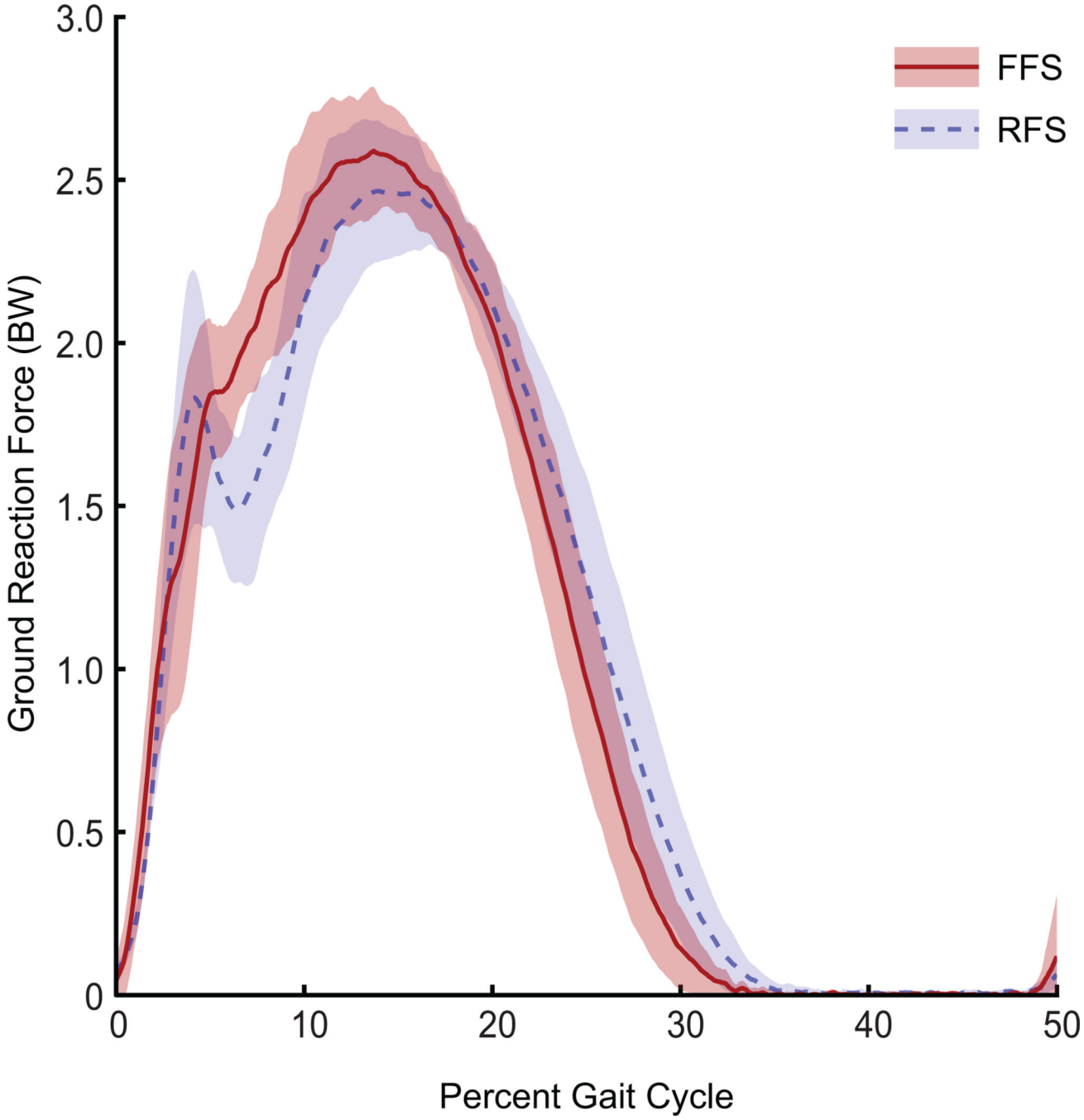

Figure 4.

Vertical ground reaction forces normalized by body weight. Represented are the ensemble average ± one standard deviation of the vertical ground reaction forces for forefoot striking (FFS, solid red) and rearfoot striking (RFS, dashed blue) runners. The time between initial contact and the peak vertical ground reaction force was classified as early stance. The RFS runners demonstrated an additional impact peak.

Table 1

Normalized electromyography signals during the late swing phase of running at 4 m/s. Presented are the mean ± one standard deviation for the root mean square (RMS) values from forefoot striking (FFS) and rearfoot striking (RFS) runners and the associated p-values.

Late Swing Phase	**RMS EMG Activity**		
Muscle	***RFS***	***FFS***	***p-value***
Tibialis Anterior	1.45 ± 0.59	0.66 ± 0.23	**0.001**
Gastrocnemius Medialis	0.28 ± 0.14	0.75 ± 0.46	**0.004**
Gastrocnemius Lateralis	0.33 ± 0.13	0.74 ± 0.35	**0.001**
Soleus	0.25 ± 0.07	0.22 ± 0.10	0.395
Rectus Femoris	0.80 ± 0.36	1.33 ± 0.91	0.077
Vastus Medialis	1.07 ± 0.26	0.72 ± 0.41	**0.032**
Vastus Lateralis	1.11 ± 0.49	0.72 ± 0.40	0.064
Medial Hamstrings	1.82 ± 0.59	1.90 ± 1.48	0.862
Lateral Hamstrings	2.20 ± 0.95	1.42 ± 0.46	**0.028**
Gluteus Medius	1.17 ± 0.79	0.80 ± 0.38	0.220

Table 2

Normalized electromyography signals during the early stance phase of running at 4 m/s. Presented are the mean ± one standard deviation for the root mean square (RMS) values from forefoot striking (FFS) and rearfoot striking (RFS) runners and the associated p-values.

Early Stance Phase	**RMS EMG Activity**		
Muscle	***RFS***	***FFS***	***p-value***
Tibialis Anterior	0.68 ± 0.61	0.84 ± 0.71	0.590
Gastrocnemius Medialis	1.46 ± 0.43	1.58 ± 1.05	0.714
Gastrocnemius Lateralis	2.11 ± 1.13	1.87 ± 0.65	0.544
Soleus	1.92 ± 0.34	1.46 ± 0.59	0.032 [a]
Rectus Femoris	3.63 ± 1.96	3.09 ± 3.12	0.624
Vastus Medialis	4.46 ± 0.94	3.70 ± 2.27	0.315
Vastus Lateralis	4.40 ± 1.75	3.80 ± 1.49	0.407
Medial Hamstrings	0.57 ± 0.25	0.97 ± 0.75	0.102
Lateral Hamstrings	0.93 ± 0.38	1.10 ± 0.57	0.400
Gluteus Medius	2.26 ± 0.88	2.90 ± 1.27	0.202

[a] Correlated with late swing phase RMS activity