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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.

1. 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

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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.

2. Methods

2.1. 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 warmup for a minimum of five minutes to get accustomed to running on the treadmill. Following warmup, 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.

2.2. 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 (Fig. 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

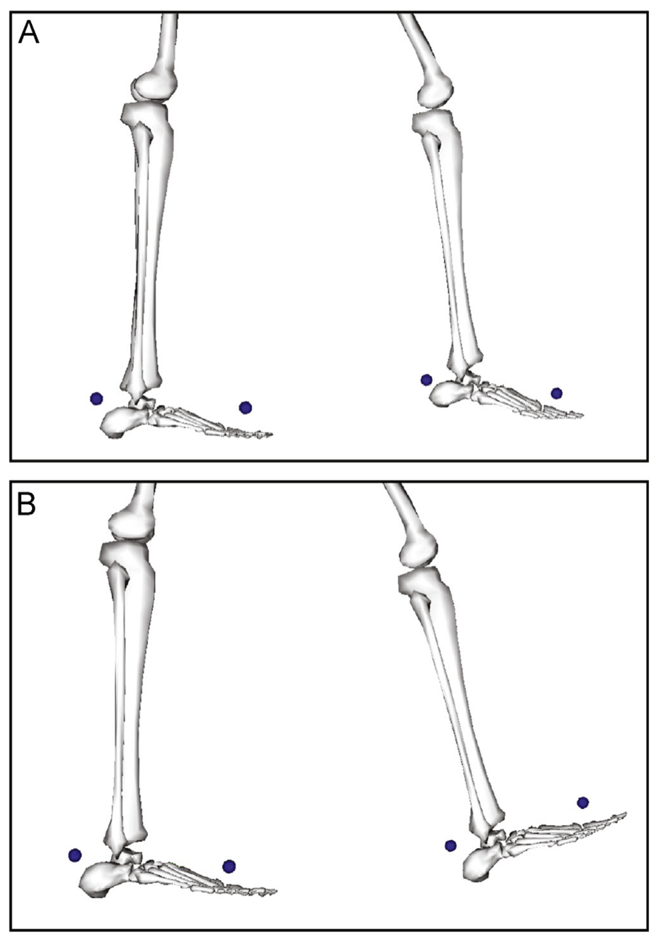

Fig. 1. (A) Segment and marker positions for a forefoot striking (FFS) runner during a standing trial (left) and at initial contact during running. (B) Segment and marker positions for a rearfoot striking (RFS) runner during a standing trial (left) and at initial contact during running. Runners were 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.