Mid/Forefoot Strike Versus Rearfoot Strike During Running: An Inverse Dynamics Study

BL Winsor and KR Williams
Biomedical Engineering Graduate Group & Exercise Biology Program
UC Davis, Davis, CA 95616 USA

Introduction

Previous research has shown different ground reaction forces (GRF’s) and kinematics are generated according to the position of the foot at contact: rearfoot, midfoot, and forefoot (Cavanagh & LaFortune, 1980, Soutas-Little et al., 1987). While differences in GRF’s and kinematics are well documented, how footstrike patterns are related to internal joint kinetics and muscle activity are less well understood. This study was designed to identify the differences in the resultant joint forces and net muscle moments due to footstrike position by evaluating the dynamics during mid/forefoot strike (MST) and rearfoot strike (RST) running. To further understand the factors that influence internal kinetics, an electromyographic (EMG) analysis of lower extremity muscles was also done.

Methods

Volunteers for this study were nine males and six female runners between the ages of 18 and 40 currently training and injury free. Subjects first participated in a practice session where continuous video feedback was used to enable each runner to comfortably run at 4.47 m•s⁻¹ using each footstrike pattern. EMG, ground reaction force, and joint kinetics data were collected during a second experimental session on a different day. A Noraxon Telemyo telemetry system using surface electrodes and sampled at 600 Hz was used to collect muscle activity patterns for the rectus femoris, vastus medialis, biceps femoris, tibialis anterior (TA), peroneus longus, gastrocnemius (GAS), and soleus (SOL) muscles. Ground reaction forces data, obtained from a Kistler force platform at 600 Hz, were combined with 3D video data, collected at 200 Hz from a Motion Analysis Expertvision system, using Kintrak™ software to provide measures of lower extremity joint forces and net muscle moments during running with each footstrike pattern. Five trials were obtained for each footstrike pattern, with the order of the initial footstrike pattern used randomized among subjects.

Anatomical segment coordinate systems (SCS) were developed for the foot, shank, and thigh segments based on the location of the reflective markers, and a transformation matrix was determined that allowed the location of joint centers to be identified from the surface markers. Kinematic and kinetic data were generated for the hip, knee and the ankle for three components of motion. Variables were extracted from each trial and then averaged within subject for the RFT and MFT conditions. The magnitudes and times of peak values were obtained prior to and during support. Values at footstrike and toe-off were also obtained, along with integrals of EMG and kinetic measures for specific time periods before and after footstrike.

Because of the large number of variables included in this analysis, a factor analysis was used to reduce the sets of variables to smaller groups. The variables were grouped into three categories, kinetics (GRF and inverse dynamics), muscle activity (EMG), and kinematics. A factor analysis was applied to each of these groups and within each group factors with eigenvalues greater than 1 were subsequently analyzed statistically using a t-test comparing the RST and MST conditions. To aid in understanding the meaning of significant differences for the selected factor variables, individual variables of interest within each factor were statistically analyzed and evaluated relative to footstrike condition.
**Results and Discussion**

Foot angles with the ground averaged 23.3° for RST and 0.1° for MST, confirming that two different footstrike patterns were achieved. Kinematic variables generated nine factors, with the variables separated by joint motion and temporal characteristics. One kinematics factor, related to ankle plantarflexion angle and the angular velocity of the ankle in the plantarflexion/dorsiflexion direction, showed significant differences between MST and RST patterns.

As expected, RST trials showed the ankle to be more dorsiflexed prior to and at footstrike, with plantar flexion occurring during the first 25% of support. In MST the ankle was more plantarflexed prior to and at footstrike, with only dorsiflexion occurring after footstrike. After the first 25% of support, the two patterns were similar through the remainder of the support time. Figure 1 illustrates this result (all figures are averages across all trials for all subjects within a condition). Differences in ankle inversion/eversion were limited to a slightly more inverted position in MST at footstrike and a more rapid maximal eversion speed. No differences were found in kinematic for the knee or hip joints.

Three significant EMG factors were identified, one comprised mainly of TA variables, one for GAS activity prior to foot strike, and one for SOL activity prior to foot strike. The TA muscle (Figure 2) showed significantly greater activation for RST compared to MST prior to footstrike. Once the foot had contacted the ground, the EMG patterns were not significantly different. The GAS muscle was activated earlier prior to footstrike in MST compared to RST, but no significant differences were apparent during support. Though the factor including SOL activity showed significant differences between conditions, none of the individual variables with high weightings in this factor were significantly different.

While both the GAS and TA muscles were activated during late swing, the greater level of activity in the TA in RST and the earlier onset of GAS in MST are likely to be the cause of differences in ankle angle at footstrike. The SOL muscle apparently does not play the same role as the GAS prior to footstrike since it did not also show early activation for either footstrike condition. Activity of GAS, SOL, and TA before and after footstrike combine to provide stability in the ankle joint during early support. As with the kinematic data, no differences in EMG patterns were evident for muscles about the knee and hip.

Of the nine kinetic factors, only one, including ground reaction forces and joint forces along the y (A-P) and z (vertical) axes and the joint moments about the x (flexion/extension) axis prior to foot strike, showed significant differences between conditions. MST generated significantly greater forces at an earlier time during support compared to the RST condition, while moments about the x-axis were
significantly greater during RST. As with previous studies comparing GRF's for different running footstrike patterns, MST was characterized by a two-peak braking force and a single peak vertical force, with RST showing a single peak braking force and a double peak vertical force. These same characteristics were also present in the A-P and vertical joint reaction forces at the ankle and the knee, with similar but less defined patterns at the hip.

Flexor/extensor moments about the x-axis (Figure 3) were significantly different between conditions during the first 25% of support. The dominant net plantarflexor ankle muscle moment showed a brief dorsiflexion moment immediately after footstrike in RST but not in MST. The net flexor RST knee moment at footstrike quickly turned extensor and was significantly greater than the MST moment during the first 25% of support. The knee moment remained flexor in MST during the first 20% of support. The ankle also showed a marked eversion moment in MST that was not observed in RST, which showed an exclusively inversion moment.

The vertical and A-P two-peak force patterns can be associated with motion of the foot/ankle during support. At footstrike in RST the ankle joint begins to plantarflex, adduct (from a slightly abducted position), and evert. At or very near the time the initial vertical ground reaction force peak occurs the ankle ends its period of plantarflexion and an adduction motion changes to an abduction one. At the same time further up the leg, peaks occur in the vertical forces at the ankle, knee, and hip, and the net muscle torque about the ankle changes from dorsiflexor to plantarflexor. During this time, A-P forces continue to increase and the foot continues to evert. During the time the ankle is plantarflexing there is a net dorsiflexor muscle torque, and when the ankle begins to dorsiflex the net moment is plantarflexor. The driving force for the movement comes from the inertia of the body at foot contact, with muscles controlling the movements at the ankle, not causing them. In MST, the second A-P force peak coincides with the end of rapid eversion. While the foot continues to evert slightly, it does so at a much slower speed. The ankle adducts at footstrike from a neutral position, and this changes to abduction at the time of the first A-P force peak and changes back to a adduction motion about the time of the second anteroposterior force peak. The first A-P peak corresponds to a positive mediolateral peak in the joint forces, and the second peak occurs at the same time as a negative mediolateral joint force peak.

The results of this study show that different footstrike patterns in running are not only associated with different ground reaction force patterns, as has been shown in previous studies, but also with different patterns of movement and muscle activity in lower leg and different patterns of joint forces and muscle moments in the ankle and knee. Lower extremity kinetics for the RST conditions were similar to those previously shown by McClay and Manal (1999). Differences between footstrike conditions were found prior to and through the first 25% of the support period, after which patterns were very similar. While kinematic and EMG differences were primarily limited to the ankle joint, differences in the magnitude and pattern of vertical and A-P joint forces were found in the hip, knee and ankle. It appears that inverse dynamics techniques can pick up some of the subtle differences in kinetic patterns exhibited during the footstrike period in running. Future studies might examine similar measures in specific individuals or groups of runners to see if variations in lower extremity kinetics can be associated with specific types of injuries.