MUSCLE CONTRIBUTIONS TO MEDIOLATERAL MASS CENTER ACCELERATION DURING RUNNING

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INTRODUCTION

During normal running, the net mediolateral ground reaction force is relatively small, with peak forces typically between 10-30% of body weight [1]. Yet, previous studies have highlighted that humans are dynamically unstable in the mediolateral direction during walking [2], and active mechanisms that control foot placement are needed to maintain mediolateral stability [3]. Other studies suggest that the hip abduction moment of the stance-leg may also be important for maintaining stability during walking [4]. Pandy et al. have created and analyzed muscle-actuated simulations to provide the first estimates of muscle contributions to mediolateral acceleration of the mass center during walking [5], yet little is known about how muscles act to accelerate the body mass center in the mediolateral direction during running.

The purpose of this study was to determine how muscles contribute to mediolateral acceleration of the body mass center over multiple strides during running at 3.96 m/s (6:46 min/mile). To achieve this, we developed and analyzed three-dimensional muscle-actuated simulations of running that included 92 musculotendon actuators representing 76 muscles of the lower extremities and torso.

METHODS

We collected marker trajectories and ground reaction forces of a single healthy male subject (height 1.83 m, mass 65.9 kg) running on a treadmill and used these data to generate subject-specific simulation of 14 strides. The subject ran at 3.96 m/s, which was three times his self-selected walking speed. The simulation was generated using OpenSim [6]. A 12 segment, 29 degree-of-freedom musculoskeletal model (Fig. 1) was scaled to match the subject's anthropometry. An inverse kinematics algorithm solved for the joint angles that best matched the subject's motion. Joint moments were calculated using a residual reduction algorithm (RRA) [6]. The computed muscle control algorithm [7, 8] was used to compute the muscle excitations required to track the kinematics produced by RRA. An induced acceleration analysis was performed to determine the contributions of individual muscles to the acceleration of the body mass center, as detailed in our previous study [9].

RESULTS AND DISCUSSION

During running, the average mediolateral acceleration is relatively small, with an overall mass center acceleration during stance of 0.13 m/s^2 medially (i.e., acceleration of the mass center to the right during left foot stance). This small net acceleration is a result of many muscles acting against each other to reduce motion of the body mass center in the mediolateral direction.

Gluteus medius, gluteus minimus, soleus, and gastrocnemius were the largest contributors to mediolateral acceleration of the body mass center during the stance phase of running.

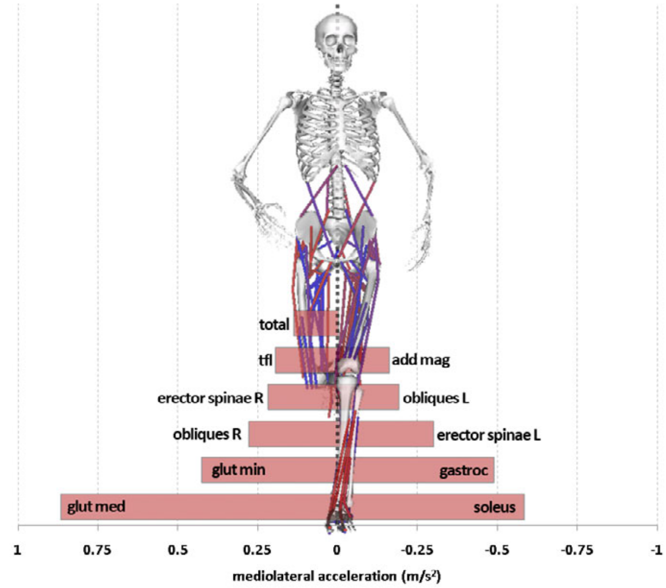

Figure 1: Average contribution to mediolateral acceleration of the mass center during left foot stance phase over 14 strides. (Note: Positive mediolateral acceleration is to the model's right and negative is to the model's left).

Gluteus medius and gluteus minimus accelerated the body mass center medially (i.e., to the right during left foot stance), while the ankle plantarflexors accelerated the mass center laterally (i.e., to the left during left foot stance). The erectors spinae and obliques, muscle groups that cross the back joint and control torso motion, contributed nearly equal and opposite accelerations to yield a small net mediolateral contribution.

Over 14 steps in the same subject, the standard deviation of muscle contributions to mediolateral mass center acceleration during stance phase was also relatively small. The maximum RMS of the standard deviation was ±0.11 m/s^2 in the quadriceps muscle group (Fig. 2, quadriceps). The RMS of the standard deviation for the total mediolateral acceleration of the mass center was ±0.25 m/s^2 (Fig. 2, total).

CONCLUSIONS

The ankle plantarflexors, which are acting to provide the majority of propulsion and support, also accelerated the body mass center laterally, while gluteus medius and gluteus minimus acted to counterbalance the plantarflexors by accelerating the mass center medially. These results are consistent with studies of both walking [5] and preliminary results for running [10]. However, unlike previous studies, our model included the effects of arms and a torso, which revealed that the left and right erector spinae and obliques tended to contribute equal and opposite accelerations to the body mass center acting to minimize mediolateral motion of the torso. Previous studies have revealed that propulsion and support of the body mass center during running is dominated by contributions from one or two muscle groups [9, 11]. In contrast, mediolateral acceleration of the mass center consists of contributions from many different contributors yielding a small net acceleration.

Several limitations should be kept in mind when interpreting our results. We analyzed a single subject at a single speed over multiple strides, thus the results do not represent a general running strategy. This analysis will be applied to data collected on multiple subjects at multiple running speeds to more thoroughly characterize muscle actions during running. Additionally, our model did not include knee ab/adduction or subtalar motion. When modeled, these degrees of freedom required significant assistance from ideal joint torque actuators to track measured kinematics. However, the model does not represent any of the passive structures that stabilize the joint and limit motion of these degrees of freedom. In future studies, modeling these passive structures will be important to accurately characterize their effect on muscle contributions to mediolateral mass center accelerations.

We have created three-dimensional muscle-actuated simulations of the running gait cycle and quantitatively described how individual muscles accelerate the body mass center in the mediolateral direction. To promote the utilization and acceptance of simulations in movement science our simulation is freely available in OpenSim [6] (simtk.org/home/RunningSim), so others may reproduce our results, perform additional analyses, and gain further insight into running dynamics.

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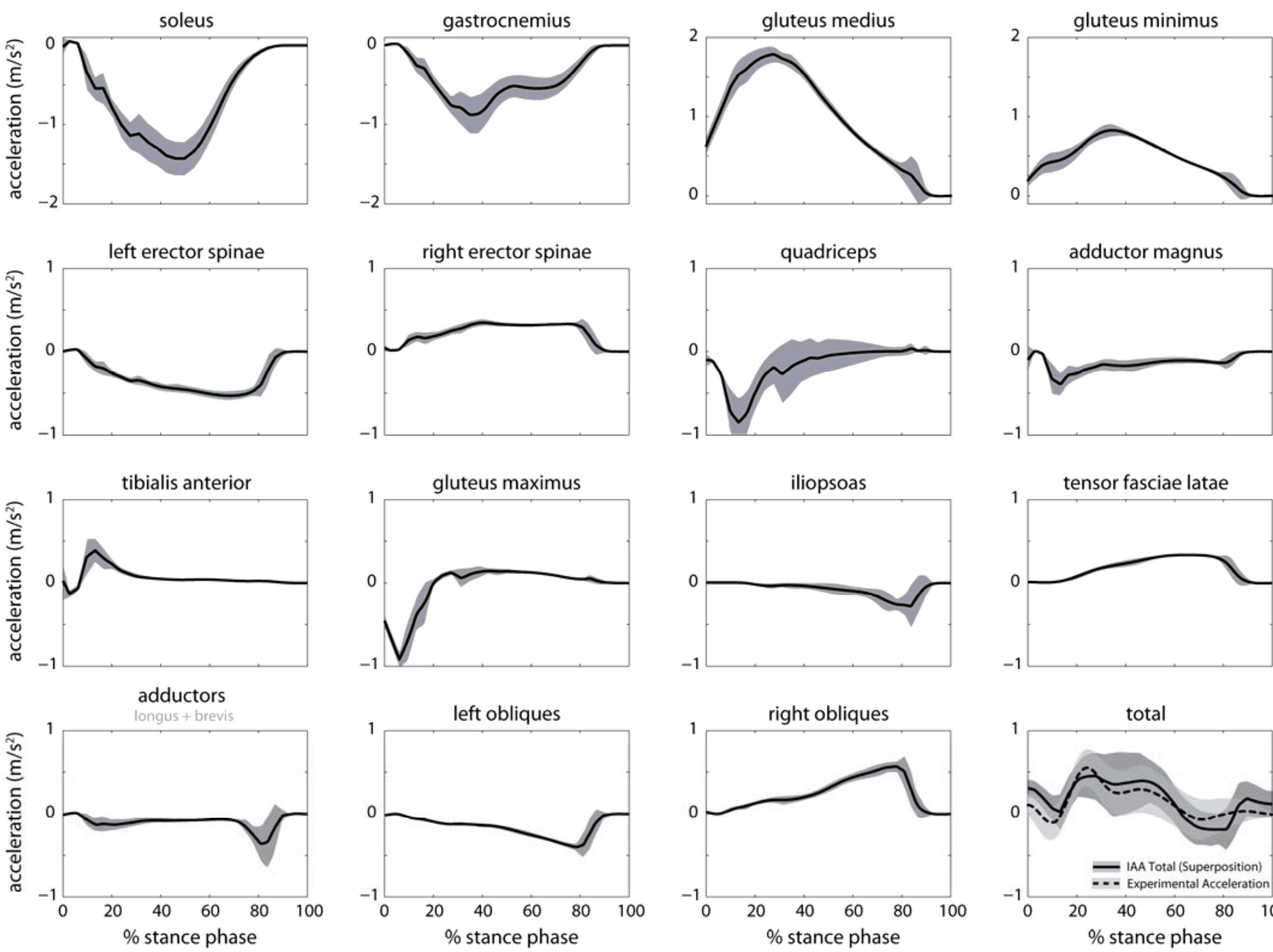

Figure 2: Individual muscle contributions to mediolateral acceleration of the mass center during the left foot stance phase of running. Solid line represents the mean and gray area represents ±1 standard deviation over 14 steps.