FIBER OPERATING REGIONS OF HUMAN LOWER LIMB MUSCLES DURING WALKING AND RUNNING

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INTRODUCTION

The force-length relationship of muscle is one of the most important and long-standing tenets of neuromuscular physiology [1]. When short, the active force a muscle fiber can generate increases with length, until it plateaus near the optimal fiber length. When longer than the optimal fiber length, the active force producing capacity of the fiber decreases. To understand the ways in which the force-length property is related to the function of muscles during human movement it is necessary to know the operating length of the muscle relative to their optimal length.

Experimental methods for measuring fiber operating length are typically invasive or difficult to use during motions like walking or running [2]. Thus, computer models that characterize muscle architecture, muscle-tendon paths, and joint kinematics are important tools for studying the link between muscle structure and function. The goal of this study was to compare fiber operating regions of key lower limb muscles during two types of gait: walking and running.

METHODS

We used a computer model of the musculoskeletal system that characterizes the geometry of bones, the kinematics of joints, and the lines of action and force generating properties of lower limb muscles (Figure 1) [3]. Each muscle was characterized by four parameters: optimal fiber length, maximum isometric force, pennation angle, and tendon slack length. These generic properties of muscle and tendon were scaled to represent the architecture of each muscle-tendon unit. The muscle architecture data used to create this model included a measurement of the relationship of between fiber length and joint angle [4]. This feature enabled us to use this model to examine fiber length as a function of joint kinematics.

The subject was a healthy male and an experienced runner (height 1.80 m, mass 63.5 kg). Walking and running data were measured at 1.5 m/s and 5.0 m/s, respectively. The positions of 54 markers were measured using an eight-camera motion capture system (Vicon; Oxford Metrics Group, Oxford, UK). Ground reaction forces were measured with a force-plate instrumented treadmill (Bertec Corporation, Columbus, OH, USA).

We scaled the computer model to the subject’s anthropometry based on marker locations. Muscle architecture parameters were scaled so that the ratio of muscle to tendon remained constant in the scaled segment. An inverse kinematics algorithm determined the joint angles of the model that best tracked the subject’s measured motion [5]. We filtered the joint angles at 6Hz using a finite-impulse response (FIR) filter to account for the effects of noisy marker data on the inverse kinematics calculation.

We calculated the mean feasible operating region of normalized fiber length over walking and running gait cycles. For the motion measured the trajectory of normalized fiber length will fall in this region, no matter the activation pattern. The elasticity of tendon allows muscle fibers to shorten when they produce active force, even as the total muscle-tendon length is constant. The feasible operating region for each muscle at a prescribed joint configuration is the difference between the normalized fiber length calculated with the muscle at maximum and zero activation. Muscles with long tendons relative to optimal fiber length produce a wide operating region because a change in tendon length has a proportionally larger effect on the fiber length. In both gaits we identified six right leg gait cycles, beginning and ending at heel-strike based on the vertical ground reaction force, and calculated the mean operating region of the six cycles for each muscle in the model.

Figure 1: Three-dimensional musculoskeletal model of the lower limbs [3] during walking (left, 1.5 m/s) and running (right, 5 m/s) gait.
RESULTS AND DISCUSSION

Fiber operating regions during walking and running were calculated for 11 lower limb muscles, a subset of which is reported here (Figure 2).

During the stance phase of both walking and running the operating regions of soleus and gastrocnemius medialis began near the plateau of the force length curve and stretched past optimal length during mid-stance. In late stance the fibers shortened rapidly as the ankle plantarflexed. In both gaits, soleus reached a minimum fiber length shortly after toe off. Gastrocnemius lateralis, however, also crosses the knee joint. Thus, a rapid increase in knee flexion after toe off caused the fibers to continue to shorten until mid swing.

The operating region of biceps femoris long head began near optimal length at heel strike then shortened throughout stance in both walking and running. Minimum fiber length occurred shortly after toe-off during walking, but was delayed in running. Minimum fiber length of biceps femoris long head was lower during running due to increased knee flexion and hip extension.

The operating regions of rectus femoris and vastus lateralis were similar to changes observed in knee flexion angle during the two gaits. Though rectus femoris also crosses the hip, changes in knee angle strongly influenced changes in fiber length, producing longer fibers during stance, delayed fiber lengthening relative to toe off, and a higher maximum fiber length during swing in running than in walking.

CONCLUSIONS

In this study, we investigated the variations in force-length operating regions for lower limb muscles during walking and running. Differences in joint range of motion and timing of toe off produced changes to the shape of operating regions, particularly the value and timing of maxima and minima. The largest changes occurred in biarticular muscles since changes to kinematics at two joints affect muscle-tendon length.

These results shed light on the role of the force-length curve during gait, but muscle force is also dependent on shortening velocity. Future work will include the force-velocity property in the calculation of fiber operating region. We will also incorporate EMG recording of muscle activity to determine the particular normalized fiber length trajectory that each muscle takes within its operating region.

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REFERENCES


Figure 2: Mean feasible operating region of normalized fiber length for soleus, gastrocnemius lateralis, biceps femoris long head, rectus femoris, and vastus lateralis, for six gait cycles at two speeds. For the joint kinematics measured, any activation pattern will produce a normalized fiber length in these ranges.