POTENTIAL OF MUSCLES TO INFLUENCE FORWARD PROGRESSION DURING THE SINGLE-SUPPORT PHASE OF NORMAL GAIT

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INTRODUCTION

Elderly persons and persons with movement disorders usually walk more slowly than young, unimpaired individuals. Inadequate muscle strength and poor intermuscular coordination are potential causes of diminished walking speed. Unfortunately, the influences of individual muscles on forward progression during walking are not well understood. Previous studies suggest that ankle plantarflexion moments during the push-off phase of the gait cycle, presumably generated primarily by soleus and gastrocnemius, contribute to forward progression [1, 2]; however, little is known about the roles other muscles might play.

As a first step toward understanding how individual muscles influence forward progression in slow or impaired gait, we identified the key contributors to forward progression during the single-support phase of normal gait. To do this, we perturbed the excitation patterns of major extensor muscles of the lower extremity (i.e., soleus, gastrocnemius, vasti, rectus femoris, gluteus maximus, and hamstrings) and computed the resulting changes in the forward displacement of the center of mass of the body. The results clarify some of the potential causes of diminished walking speed and provide insight into what therapies and muscle coordination strategies may help increase walking speed.

METHODS

The dynamic optimization solution for normal gait obtained by Anderson and Pandy [3] was used as the basis of our analysis. The body was modeled as a 10-segment, 23-degree-of-freedom articulated linkage actuated by 54 Hill-type muscles. The back joint and hips were modeled as ball-and-socket joints. The knees, subtalar, and metatarsal phalangeal joints were modeled as hinges. Muscle parameters and path geometries were based on data reported by Delp [4]. The interaction between the foot and the ground was modeled using five stiff spring-damper units distributed under the sole of the foot. Activation dynamics was modeled using a first-order ordinary differential equation that simulated an activation rise time of 0.022 s and a fall time of 0.222 s. The time history of each muscle's excitations during single-support stance was represented by 15 control nodes that were linearly interpolated (Fig. 1). Excitations were allowed to vary continuously between 0.01 (minimum excitation) and 0.99 (full excitation). The joint angular displacements, ground reaction forces, and muscle excitation patterns predicted by the dynamic optimization solution were similar to those obtained from five healthy subjects who walked at an average speed of 1.35 m/s [3].

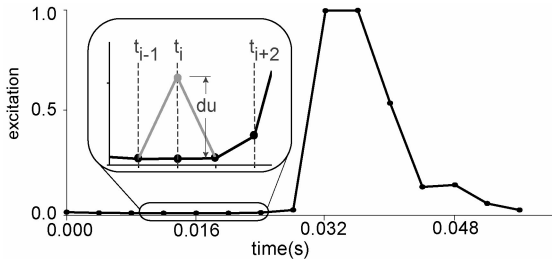

Figure 1: Perturbation of a muscle excitation history

The potential of a muscle to influence forward progression was quantified by evaluating the partial derivative of the position of the center of mass in the direction of forward progression (X) with respect to that muscle's excitation level (u). The partial derivative was evaluated using central differences by perturbing the excitation level of a control node at t_i, numerically integrating the equations of motion from t_{i-1} to t_{i+2}, and computing the resulting position of the center of mass in the direction of forward progression:

$$\left.\frac{\partial X}{\partial u}\right|_{t_i} = \frac{X_{t_{i+2}}(u+du) - X_{t_{i+2}}(u-du)}{2 \cdot du}, \qquad (1)$$

where du is the size of the perturbation (Fig. 1). The size of du was chosen to be 0.01 (i.e., about 1% of maximum excitation). This perturbation size was small enough that the simulation retained the same basic coordination as the unperturbed simulation and large enough that changes in center of mass position were several significant

digits above the precision of the integrator. A variable-step Runge-Kutta-Feldberg 5-6 integrator with an error tolerance of 10^{-5} was used to perform the integrations. Doubling or halving *du* had negligible impact on the results.

RESULTS

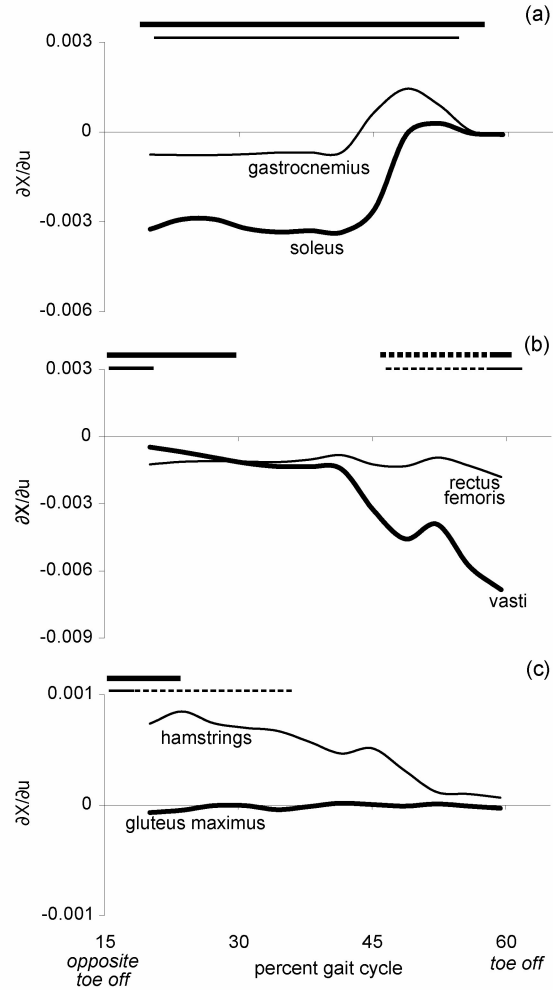

Figure 2: Influence of (a) ankle, (b) knee, and (c) hip extensor muscles on forward progression. Bars indicate average electromyographic activity at normal walking speeds (solid) and increased activity at fast walking speeds (dashed) [5] for gastrocnemius, rectus femoris, and hamstrings (thin lines) and soleus, vasti, and gluteus maximus (thick lines).

Few extensor muscles of the stance leg had the potential to increase forward progression during the single-support phase of gait (Fig. 2). During most of single-support, increasing the excitations of the ankle extensors reduced forward progression (Fig. 2(a)). In late single-support, at approximately 45% of the gait cycle, the influence of the ankle extensors switched to promoting forward progression. Increasing the excitation of gastrocnemius, a biarticular ankle-extensor/knee-flexor, enhanced forward progression more than increasing the excitation of soleus, a uniarticular ankle extensor. The ankle extensors are usually excited at low levels during early and mid stance, and are highly excited during late stance; the timing of excitation of these muscles does not change with increasing walking speeds [5].

Increasing the excitations of the knee extensors reduced forward progression (Fig. 2(b)). The inhibitory influence of vasti, a uniarticular knee-extensor, was greater during late stance than that of rectus femoris, a biarticular knee-extensor/hip-flexor. At normal walking speeds, these muscles are usually active only very early in single-support; as walking speed increases, they are also excited prior to toe-off [5].

The influences of hip extensor muscles on forward progression were mixed (Fig. 2(c)). Altering the excitation of the gluteus maximus, a uniarticular hip extensor, had little effect on forward progression. Increasing the excitation of hamstrings, a biarticular hip-extensor/knee-flexor, enhanced forward progression throughout single-support. At normal walking speeds, these muscles are usually active only during early single-support. At fast walking speeds, however, hamstrings excitation continues well into single support [5].

DISCUSSION

Of the major extensor muscles, the muscles with the greatest potential to increase forward progression were gastrocnemius and hamstrings, which both generate knee flexion moments. Hamstrings was the only major muscle group that had the potential to contribute positively to forward progression throughout single-support. On the other hand, muscles that produce a knee extension moment, such as the vasti and rectus femoris, had a negative influence on forward progression throughout single-support.

The results of this study suggest that over-activity of the ankle extensors (soleus and gastrocnemius) during early and middle single-support and over-activity of the knee extensors (vasti and rectus femoris) at any time during single-support could hinder forward progression and lead to diminished walking speed. The results further indicate that increasing the activity of the ankle extensors during late stance, particularly that of gastrocnemius, and increasing the activity of hamstrings would be an effective coordination strategy for increasing walking speed. Assuming an appropriate coordination pattern for these muscles is achieved during gait, therapies that strengthen the hamstrings muscle group and gastrocnemius might also be effective for improving walking speed.

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