GLUTEUS MAXIMUS AND SOLEUS COMPENSATE FOR SIMULATED QUADRICEPS ATROPHY AND ACTIVATION FAILURE OVER A RANGE OF WALKING SPEEDS

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INTRODUCTION
Lower extremity muscles perform two main tasks during walking: generation or maintenance of forward progression and vertical support of the body mass center [1]. Not surprisingly, muscle weakness may impair someone’s ability to maintain a normal gait. For example, quadriceps muscle weakness in some populations has been correlated with a decreased walking speed when compared to healthy individuals [2]. Quadriceps weakness may be a result of muscle atrophy and/or reduced voluntary muscle activation. Quadriceps strength deficits can be as high as 64% compared to the uninjured side [3] and quadriceps activation deficits may approach 34% [4]. While quadriceps weakness has been correlated with a slower walking speed, the important cause-effect relationships between abnormal muscle function and reduced gait speed remain unknown.

The purpose of this study was to use muscle-driven simulations to estimate the muscle compensations needed to maintain normal kinematics over a range of walking speeds in response to quadriceps weakness (atrophy and activation failure).

METHODS
Six healthy subjects (2M/4F, Age: 21.0 ± 2.3 years) provided IRB-approved written informed consent. Each subject walked at a self-selected (1.31 ± 0.14 m/s), slow (1.08 ± 0.14 m/s), and fast (1.70 ± 0.25 m/s) speed while motion data were collected at 150 Hz using an 8-camera Vicon MX-F40 system and the Point-Cluster Technique [5]. Ground reaction forces were obtained from six force plates sampled at 600 Hz. Surface electromyography was simultaneously collected (1500 Hz) from the bilateral lower extremity muscles. We simulated one gait cycle for each subject and gait speed using OpenSim [6]. Computed muscle control [7] was used to calculate the muscle excitations and forces in all lower extremity muscles that produced a coordinated simulation of the subjects’ gait. An induced acceleration analysis was then performed to determine the contributions of individual muscles to the forward progression and vertical support of the body mass center [8]. After completing the full-strength simulations, we weakened the quadriceps (rectus femoris and vasti) of one stance leg in three ways: 1) decreasing the quadriceps’ peak isometric muscle force to 40% of normal (Atrophy Only), 2) constraining the peak activations of the quadriceps to 65% of the peak values that were calculated during the full-strength simulation (Activation Failure Only) and 3) a combination of simulated atrophy and activation failure (Atrophy + Activation Failure). We then forced the simulations to track normal gait kinematics, re-calculated muscle forces and contributions to progression and support in the weakened models, and identified changes in muscle forces and contributions to progression and support between the full-strength simulation and the simulations with quadriceps weakness.

RESULTS AND DISCUSSION
Of the major lower extremity muscle groups investigated, the gluteus maximus and soleus muscles displayed the greatest ability to compensate for simulated quadriceps weakness at all gait speeds by increasing force output and contributions to progression and support to maintain normal gait.

Muscle Forces
The gluteus maximus generated more force in early stance to compensate for quadriceps weakness, and increased its force output with increasing gait speed (Figure 1). Compensation by the gluteus maximus was greatest in response to the combination of simulated atrophy and activation failure of the quadriceps at all gait speeds. In contrast, we found that the soleus generated more force in late stance and decreased its force output with increasing gait speed.
Compensation by the soleus was greatest in response to activation failure of the quadriceps, except for the slow gait speed, in which compensation was greatest in response to combined atrophy and activation failure (Table 1). Figure 1: The effect of simulated quadriceps weakness on the force generated by the gluteus maximus over a range of gait speeds.

Contributions to progression and support
The gluteus maximus contributed more to slowing forward progression (braking) and providing vertical support in early stance to compensate for quadriceps weakness. Contributions to support increased with gait speed, but contributions to braking decreased when gait speed increased from self-selected to fast (Table 1). The soleus contributed more to progression and support in late stance to compensate for quadriceps weakness. Contributions to progression and support increased from a slow to a self-selected gait speed, but decreased from a self-selected to a fast gait speed.

Previous researchers have investigated muscle compensations due to weakness by simulating muscle atrophy only [9] or contributions to support and progression over a range of walking speeds [10]. To our knowledge, our study is the first use of muscle-driven simulations, albeit in healthy subjects, to investigate how lower extremity muscles could compensate for both quadriceps atrophy and activation failure to maintain normal gait kinematics over a range of walking speeds.

CONCLUSIONS
All simulations were able to track normal gait kinematics at all speeds, suggesting that it would be physiologically feasible for persons with quadriceps weakness to walk at a fast gait speed. Since persons with quadriceps weakness are known to walk slower than healthy individuals, our results indicate that other factors not simulated by our model (e.g. pain and perceptions of instability) likely contribute to reduced walking speeds in individuals with quadriceps weakness. Our findings lay the foundation for future work addressing factors that limit walking speed in pathological gait.

REFERENCES

Table 1: Peak changes in muscle force and contributions to progression and support in response to activation failure alone (†) or combined atrophy and activation failure of the quadriceps (unmarked).

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Speed</th>
<th>Peak Force (N)</th>
<th>Progression (m/s²)</th>
<th>Support (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Change due to weakness</td>
<td>Change from self-selected (SS) speed</td>
<td>% Change from SS speed</td>
</tr>
<tr>
<td>Gluteus Maximus</td>
<td>Slow</td>
<td>100.1</td>
<td>-167.6</td>
<td>-34.5</td>
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<tr>
<td></td>
<td>SS</td>
<td>132.6</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>84.5</td>
<td>181.0</td>
<td>37.2</td>
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<tr>
<td>Soleus</td>
<td>Slow</td>
<td>115.5</td>
<td>-65.7</td>
<td>-3.4</td>
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<td>SS</td>
<td>211.8†</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>268.7†</td>
<td>-127.7</td>
<td>-6.5</td>
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