BIARTICULAR MUSCLES INFLUENCE POSTURAL RESPONSES: IMPLICATIONS FOR TREATMENT OF STIFF-KNEE GAIT

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INTRODUCTION

Stiff-knee gait is a prevalent and troublesome movement abnormality among children with cerebral palsy, where peak knee flexion is diminished during swing phase. This diminished flexion has been attributed to the excessive knee extension moment produced by the rectus femoris muscle [1,2]. This muscle is a biarticular muscle crossing the hip and knee.

Rectus femoris transfer surgery, a common treatment for stiff-knee gait, reattaches the distal tendon of this biarticular muscle to a new site, such as the sartorius insertion on the tibia. This treatment aims to decrease the muscle's knee extension moment while preserving its hip flexion moment by altering the original, pre-surgical biarticular function.

Biarticular muscles play a unique role in motor control. Some suggest they function as energy conveying straps between joints [3,4]. Others suggest biarticular muscles may contribute to contact control tasks by distributing the net moments over multiple joints [4]. As a biarticular muscle, rectus femoris may offer unrecognized benefits that influence postural responses.

In this study, we used musculoskeletal modeling and forward dynamic simulation to investigate the influence of biarticular muscles in postural responses. Our goal was to compare posterior, whole-body center of mass (CoM) displacements in response to anterior support-surface translations for separate simulations of pre- and post-surgical transfer of the rectus femoris to the sartorius. We hypothesized that the pre-surgical simulation has larger peak recovery of the original CoM location relative to the support surface compared with the post-surgical one.

METHODS

We assessed the influence of rectus femoris transfer surgery on postural responses by creating dynamic simulations of a patient with cerebral palsy. A three-dimensional musculoskeletal model with 92 muscle-tendon actuators and 23 degrees of freedom was created in OpenSim (Fig. 1). The model was scaled to represent the size of the patient using previously collected gait analysis data [5,6,7]. A pre-surgical simulation was altered to represent surgical transfer of the rectus femoris to the sartorius (Fig. 1a and 1b) [7]. The foot-ground interface was modeled using elastic foundation contact and the feet were based on cadaver foot geometry [8].

The mechanism involved in maintaining an erect posture was based on a muscle stretch-reflex control model [9]. The controller's static and dynamic thresholds and reflex gain were determined using MATLAB's nonlinear least-squares optimizer algorithm for a 16s-long simulation of a quiet-standing condition for the pre-surgical model. This controller is analogous (but not identical) to monosynaptic reflexes and afferent mechanisms (e.g., muscle spindles and Golgi tendon organs) responsible for lower-level motor control, and should not be affected following surgical transfer. Thus, the same stretch-reflex controller was used for both the pre- and post-surgical simulations of quiet standing and support-surface translations.

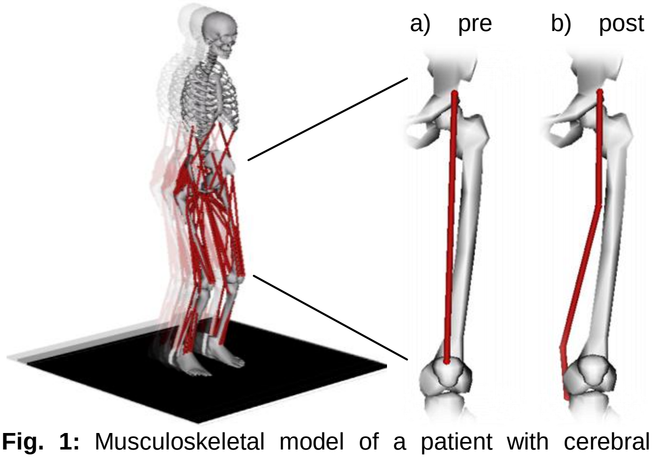

Fig. 1: Musculoskeletal model of a patient with cerebral palsy on an anteriorly translating support surface and biarticular attachments for the rectus femoris muscle (a) pre- and (b) post-surgical transfer to the sartorius.

The support-surface was translated anteriorly 10 cm over a 0.5s time range with a peak velocity of 28 cm/s and peak acceleration of 0.23g. This translation was based on experimental methods for adult subjects [10]. The adult-sized translational distance was scaled (83%) to be proportional to the size of child in this study. The simulation of support-surface translation was roughly 1.5s long, including 0.25s of quiet standing, 0.5s of translational motion, and 0.75s of recovery.

We evaluated our hypothesis regarding the peak recovery of CoM location relative to the support surface by quantifying this recovery as:

$$Recovery_{peak} = \left(1 - \frac{d_{minimum}}{d_{maximum}}\right) * 100\%$$

where $d_{minimum}$ was the minimum CoM displacement during recovery (marked as 'x' in Fig. 2) and $d_{maximum}$ was the CoM displacement at the instant the translation ended (t=0.75s). Both displacements were measured from the original CoM location relative to the support surface. For example, a peak recovery of 50% would be indicated by a $d_{minimum}$ of 4 cm following a $d_{maximum}$ of 8 cm. Moreover, a $d_{minimum}$ of 0 cm would result in 100% recovery.

RESULTS AND DISCUSSION

The pre-surgical simulation of postural response to support-surface translation had a 2.5x larger peak recovery of the original CoM location relative to the support surface compared with the post-surgical one (Fig. 2). Both cases reached a peak recovery before the end of the 1.5s simulation (t_{pre}=1.4s and t_{post}=1.2s). The pre-surgical simulation had a peak recovery of 35% and the post-surgical one had 14%. This finding supports our hypothesis that the pre-surgical simulation has larger peak recovery compared with the post-surgical one.

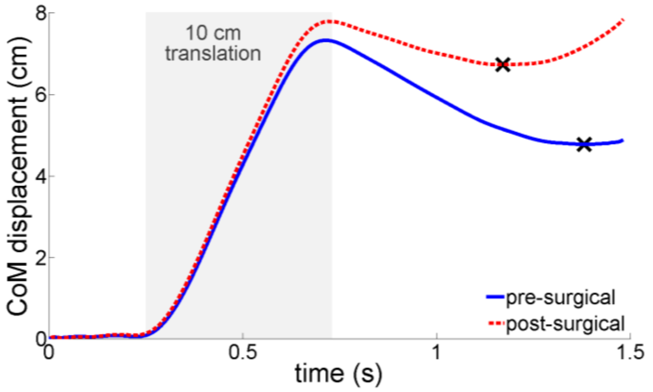

Fig 2: Posterior displacements of the original CoM location relative to the support-surface, and anterior recoveries in response to anterior support-surface translations for separate simulations of pre- and post-surgical transfer of the rectus femoris to the sartorius. The support-surface translation time is highlighted in gray. The minimum CoM displacement during recovery, $d_{minimum}$, is marked by an 'x'.

Both pre- and post-surgical simulations used a stretch-reflex controller with static (5.41) and dynamic (0.02) thresholds and a reflex gain (8.95) optimized for a 16s-long simulation of the pre-surgical model during quiet-standing. This same controller maintained an erect posture for the post-surgical model during a quiet standing condition for about 4s, or more than twice the time (1.5s) for the translational simulations.

Successful development of a stretch-reflex controller and application to a musculoskeletal model for support-surface translations has allowed for evaluation of the influence of the biarticular muscle, rectus femoris, in lower-limb postural response tasks. Our findings suggest that distal transfer of the rectus femoris results in diminished postural response compared to the original, pre-transfer case, illustrating the biomechanical advantage that biarticular muscles have in contact control tasks.

CONCLUSIONS

Patient-specific simulation is a powerful tool to investigate the role of biarticular muscles in control tasks. Future investigations will look at the influence of unilateral versus bilateral rectus femoris transfers on postural responses and potential applications to investigate biarticular muscles in other treatments (e.g., hamstrings lengthening) for other movement abnormalities (e.g., crouch gait).

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ACKNOWLEDGEMENTS

We are appreciative to the Center for Motion Analysis at the Connecticut Children's Medical Center in Hartford, CT. This research was supported by The University of Tennessee.