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Rectus femoris transfer surgery affects balance recovery in children with cerebral palsy: A computer simulation study

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ABSTRACT

Stiff-knee gait is a troublesome movement disorder among children with cerebral palsy (CP), where peak swing phase knee flexion is diminished due to over-activity of the rectus femoris muscle. A common treatment for stiff-knee gait, rectus femoris transfer surgery, moves the muscle's distal tendon from the patella to the sartorius insertion on the tibia. As a biarticular muscle, rectus femoris may play a role in motor control and have unrecognized benefits for maintaining balance. We used musculoskeletal modeling, neuromuscular control, and forward dynamic simulation to investigate the role of rectus femoris tendon transfer surgery on balance recovery after support-surface perturbations for children with CP adopting two different crouched postures. We combined both high-level supraspinal and low-level spinal signals to generate 92 muscle excitations for tracking experimental whole body center of mass positions and velocities. Stability during balance recovery was evaluated by the minimum distance between the extrapolated center of mass and base of support boundary (b_{min}) and the minimum time to reach the boundary (TtB_{min}). The balance recovery of pre-surgical simulations ($b_{min} = 2.3 + 1.1$ cm, $TtB_{min} = 0.2 + 0.1$ s) were different ($p = 0.02$), on average, than post-surgical simulations ($b_{min} = -4.9 + 11.4$ cm, $TtB_{min} = -0.1 + 0.3$ s) of rectus femoris transfers. The moderate crouch simulations ($b_{min} = 2.4 + 0.4$ cm, $TtB_{min} = 0.2 + 0.03$ s) were more stable than the mild crouch simulations ($b_{min} = 1.2 + 0.3$ cm, $TtB_{min} = 0.1 + 0.02$ s) following anterior translations of the support surface. These findings suggest that tendon transfer of rectus femoris affects balance recovery in children with CP.

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1. Introduction

Stiff-knee gait is one of the most prevalent and troublesome movement abnormalities among children with CP and its symptoms are treatable with surgery involving the rectus femoris muscle. There are approximately 573,000 individuals affected by spastic CP in the United States. Patients experiencing stiff-knee gait typically adopt energy-inefficient movements to compensate for reduced toe-clearance and avoid tripping or falling due to spastic, over active lower-extremity muscles. Stiff-knee gait is often accompanied by excessive knee flexion during stance (crouch gait) [1], which may also play a role in balance control [2]. Rectus femoris over-activity is attributed as a primary cause of stiff-knee gait [3]. Various surgical procedures can treat CP symptoms by altering the function of problematic muscles including the rectus femoris [4,5]. Rectus femoris transfer surgery is one such procedure, which aims to convert the muscle's knee extension moment to a knee flexion moment. Unfortunately, outcomes following surgery are met with variable success [6,7].

Rectus femoris is a biarticular muscle, acting as both a hip flexor and knee extensor, and may play a role in maintaining balance during dynamic tasks [8,9]. Some have suggested biarticular muscles act as energy transfer straps across joints [10]. Furthermore, others have suggested biarticular muscles play a distinct role in motor control and are among the first muscles affected in persons with CP [11]. As a biarticular muscle, rectus femoris may be important in maintaining balance and may have deleterious effects when transferred to become a knee flexor.

Recommendations for rectus femoris transfer surgeries are generally based on physical examinations along with clinical movement analysis and surgical treatments; the biomechanical consequences and outcomes following rectus femoris transfer

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surgery are rarely considered. Physical examination of a single passive joint motion does not address coordinated multi-joint movement. Clinical movement analysis characterizes the motion of limb segments, but not the individual muscle contributions causing this motion. Muscle-actuated simulations and bio-inspired control systems potentially give insights into the complex interaction between neural commands, musculoskeletal geometry, and resulting functional movements. Combining clinical movement analysis and simulation-based approaches may lead to a better understanding of biomechanical consequences of stiff-knee gait and its treatments.

The objective of this study was to determine the effect of simulated rectus femoris transfer surgery on balance recovery after support-surface perturbations for children with CP adopting two different crouched postures. We hypothesized that the stability of pre-surgical simulations would be different (i.e., have better or worse balance recovery) than post-surgical simulations. We tested this hypothesis by comparing the minimum distance from the extrapolated whole body center of mass (CoM_{extrp}) to the base of support (BoS) boundary and the minimum time for the CoM_{extrp} to reach the BoS boundary [12]. We also determined whether moderate crouched postures were more stable than mild crouched postures for balance recovery.

2. Methods

We determined the influence of the biarticular rectus femoris muscle on balance recovery in children with CP by performing the following four steps: (1) creating musculoskeletal models of children with spastic CP before and after rectus femoris transfer surgery adopting either a mild or moderate crouched posture; (2) designing a biologically-inspired, closed-loop control system for balance recovery; (3) generating forward dynamic simulations to examine balance recovery following support-surface translations; and (4) evaluating stability margins using the extrapolated center of mass position and minimum time-to-boundary of the base of support.

2.1. Musculoskeletal models

Three-dimensional musculoskeletal models with 92 muscles and 23 degrees of freedom were constructed in OpenSim [13]. The Hill-type muscle-tendon model was used as the basis for each muscle in the simulations [14]. The foot-ground contact geometry were based on 3D scans of cadaver feet [15] and ground reaction forces were modeled using elastic foundation mesh-based contact [13]. The stiffness and dissipation values were chosen based on material properties of skin (foot) and concrete (ground) materials [16]. The models were scaled to represent the size of children with spastic CP [17]. To simulate rectus femoris transfer surgery, we modified the pre-surgical models to create post-surgical ones by reattaching the distal tendon of the rectus femoris from the patella (Fig. 1a) to the insertion of the sartorius on the tibia (Fig. 1b). The tendon slack length of the transferred muscle was scaled to ensure the muscle fibers operated near their pre-surgical length ranges [3]. The tendon attachments on bones and muscle via-points are defined based on the MRI images of subjects with CP [18] and modeled using OpenSim via points. The unilateral model represented a simulated transfer on the left limb only, while the bilateral model represented a transfer on both limbs. The crouched postures of the models were selected based on average lower-extremity kinematics of children with cerebral palsy adopting mild (ankle, knee and hip angle of 13.8°, 20.9° and 17.5°, respectively) and moderate (ankle, knee and hip angle of 20.6°, 37.3° and 28.1°) crouch gait. For each model to maintain balance during forward dynamic simulations, a control system design was necessary.

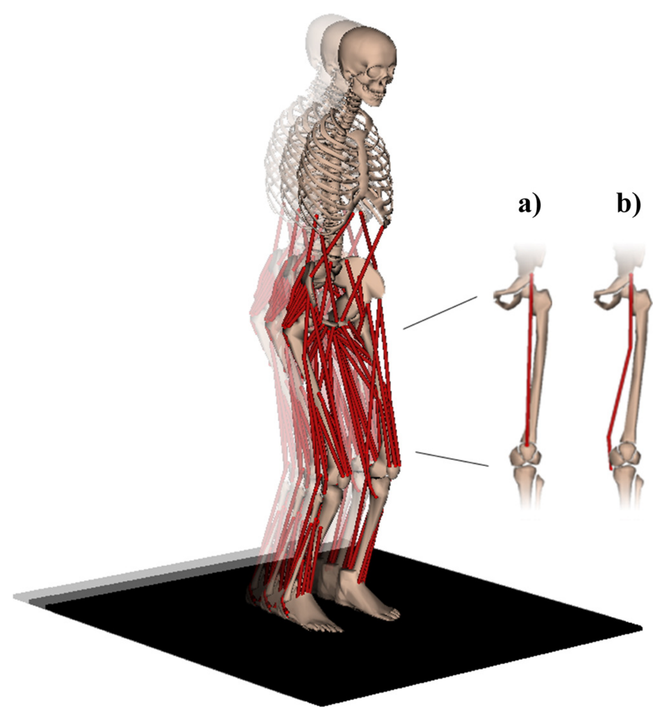

Fig. 1. Three-dimensional, 23 degree-of-freedom musculoskeletal model with 92 muscle-tendon actuators (shown in red) recovering balance on a support surface translating 7.5 cm over 0.55 s with a maximum velocity of 18 cm/s. The musculoskeletal model was used along with a biologically-inspired controller to create forward dynamic simulations of children with mild and moderate crouch to test our hypothesis regarding balance recovery following rectus femoris transfer surgery. Biarticular locations for the rectus femoris muscle are shown as (a) the pre-surgical attachment to patella and (b) the post-surgical transfer to the insertion of the sartorius on the tibia. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2.2. Biologically-inspired controller

Each musculoskeletal model used a biologically-inspired controller to track the experimental CoM displacements similar to the Central Nervous System (CNS) combination of high-level supraspinal and low-level spinal signals in controlling human balance. The high-level controller utilized computed muscle control (CMC) [19] to calculate muscle excitations (peripheral nerve action potential, which initiates the muscles excitation-to-activation process signals) to maintain a static posture despite the forces of gravity. The CMC algorithm utilizes a combination of feedback control, static optimization and forward dynamics to estimate muscles excitations required for tracking a movement [19]. The forward dynamics portion uses muscle excitations calculated from static optimization to drive a model replicating the experimental joint motion. The feedback controller ensures the muscle excitations generate a simulated movement tracking the experimental one. The low-level controller utilized a stretch reflex based on a combination of muscle spindles and Golgi-tendon organ (GTO) [20]. The muscle spindle provides the CNS with information about length and contraction velocity of muscles. The GTO provides the CNS with information about forces in muscle-tendon complex (MTC) and helps to stabilize posture. Together, these afferent mechanisms provide a simple feedback estimate of muscle-tendon length, velocity, and force for controlling postural responses (Eq. (1), Fig. 2).

$$Excitation(t) = CMC(t) + k_p[l_{MTC_{ref}}(t) - l_{CE}(\Delta t) - l_{SE}(\Delta t)] + k_d[-V_{CE}(\Delta t)] \quad (1)$$

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