Dynamic Simulation and Neuromuscular Control of Balance in Children with Cerebral Palsy: Implications for Rectus Femoris Transfer Surgery

Misagh B. Mansouri, Jeffrey A. Reinbolt
University of Tennessee, Knoxville, TN, USA

Introduction: Stiff-knee gait is a prevalent movement abnormality among children with cerebral palsy (CP). Over-activity of the rectus femoris (RF) during swing phase induces an excessive knee extension moment, and is attributed as a primary cause of this gait pattern. RF 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. As a biarticular muscle, RF plays a unique role in neuromuscular control of movement and is among the first affected muscles in the case of CP. In this study, we used neuromusculoskeletal modeling, forward dynamics simulations and biologically-inspired control algorithms to investigate the role of RF transfer surgery on balance recovery in children with CP. Moreover, we aimed to compare the ability of the CP simulations to maintain balance with that of a Normally Developing Child (NDC) simulation. We hypothesize that the NDC and pre-surgical simulations are more stable than the post-surgical ones.

Materials and Methods: We assessed influence of RF transfer surgery on balance by creating a novel closed-loop, forward dynamic simulations using our OpenSim_MATLAB interface in Simulink [1] of children with CP. In OpenSim, 3D models with 92 muscle actuators and 23 degrees of freedom were scaled to represent the size of two 10-year-old boys with mild and severe crouch postures. The pre-surgical model was altered to represent unilateral (RF transferred on one limb) and bilateral (RF transferred on both limbs) RF transfers to the sartorius. The foot-ground contact was represented using an elastic foundation contact model. We designed a closed-loop controller for maintaining the models' balance during anterior and posterior support-surface translations (7.5 cm, 18 cm/s). The controller consisted of two different levels: 1) the high-level controller used computed muscle control (CMC) to estimate muscle activations for quiet standing and 2) the low-level controller used a combination of muscle spindle and Golgi tendon organ feedback [2] to reject postural disturbances (Figure 1). We defined postural stability as the minimum distance (b_min) between the model's extrapolated center of mass (CoM) and the base of support boundary (BoS) and also the minimum time it takes for the CoM to reach BOS [3].

Results and Discussion: During quiet standing, although all models maintained balance, the NDC (b_min = 0.098m, min_TtB = 92.26s) and pre-surgical (b_min = 0.094m, min_TtB = 22.2s) simulations were more stable than postoperative ones (b_min = 0.084m, min_TtB = 11.7s). During the anterior and posterior support-surface translations, the NDC and pre-surgical simulations maintained balance while postoperative (unilateral and bilateral) simulations lost balance during posterior translations of support surface. Due to the unique role of the RF muscle as a biarticular one that flexes the hip and extends the knee, our results showed changing the RF function as a knee extensor to a knee flexor had a negative effect on balance recovery in certain simulations.

Conclusions: These findings suggest that surgical treatment of stiff-knee gait using RF tendon transfer may influence postural responses by reducing balance recovery, illustrating the unique role that RF biarticular muscle plays in neuromuscular control of movement.

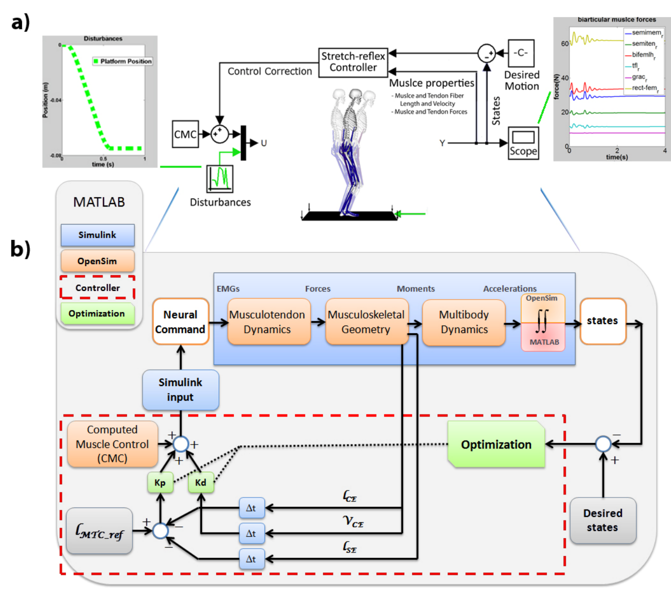

Figure 1. a) Schematic of closed-loop forward dynamic simulation and control in Simulink. b) Illustrates the algorithm inside the closed-loop, forward dynamics simulation. Gains, k_p and k_d , were selected by a non-linear least square optimization minimizing postural sway. l_{MTC_ref} is the reference muscle-tendon-complex length, l_{CE} is the contractile element (CE) length, l_{SE} is the tendon slack length, V_{CE} is the CE velocity.

References:

1. Mansouri MB, et al., *J Biomech*, 2012, 45:1517-21.
2. Kistemaker DA, et al., *J Neurophysiology,* 2013, 109:1126-39.
3. Hof AL, et al., *J Biomech*, 2005, 38:1-8.