SIMULATION-BASED TREATMENT PLANNING FOR GAIT ABNORMALITIES: VISION AND CHALLENGES

[1]Allison S. Arnold, [1]Frank C. Anderson, [1]May Q. Liu, [2]Ilse Jonkers, [1]Ayman Habib, [3]Darryl G. Thelen, and [1]Scott L. Delp
[1]Departments of Mechanical Engineering and Bioengineering, Stanford University
[2]Faculty of Kinesiology and Rehabilitation Sciences, KULeuven, Belgium
[3]Department of Mechanical Engineering, University of Wisconsin-Madison
email: asarnold@stanford.edu, web: www.stanford.edu/group/nmbl

INTRODUCTION

The management of gait abnormalities in persons with neuromuscular disorders is challenging. Theoretically, gait abnormalities can be alleviated by first identifying the biomechanical factors that contribute to abnormal movement and then *(i)* decreasing the muscle forces that disrupt normal movement (e.g., via tendon transfers or botulinum toxin injections) and/or *(ii)* increasing the muscle and ground reaction forces that have the potential to improve movement (e.g., via strengthening exercises, orthoses, or osteotomies). However, physical examination and gait analysis alone are often not sufficient to identify the cause of a patient's abnormal gait or to predict the consequences of treatments. The transformation from EMG patterns to multijoint movement is complex, and experimental approaches to infer a muscle's actions, based on the muscle's attachments, EMG activity, and measured motions of the body, cannot explain how forces produced by the muscle contribute to motions of the joints. At present, the treatment outcomes are inconsistent; some patients show dramatic improvements after treatment, while others show little improvement or get worse.

The following case study illustrates how dynamic simulation can be used, with gait analysis, to enhance our understanding of gait abnormalities and to provide a scientific basis for planning treatments. We generated a 3D muscle-actuated simulation of a subject with stiff-knee gait to determine the source of his diminished swing-phase knee flexion and to evaluate the potential efficacy of different treatments.

CASE STUDY

The subject was a 12-year-old male with cerebral palsy. Preoperatively, his peak knee flexion during swing was 33º, and he exhibited abnormal activity of the rectus femoris throughout the gait cycle. We represented the subject's musculoskeletal system by a 21-degree-of-freedom linkage that was scaled to his size and actuated by 92 muscles. We used "computed muscle control" [1] to find a set of muscle excitations that, when used to drive a simulation of the preswing and swing phases, generated gait kinematics and kinetics that closely matched the experimental data (Fig. 1). The predicted muscle excitations were consistent with the subject's measured EMG activity.

Analysis of the simulation revealed that the subject's stiff-knee gait was caused by excessive rectus femoris forces during preswing. His average knee extension and hip flexion moments in early swing were within normal limits, as were his average hip and ankle flexion moments in preswing. However, his average knee extension moment in preswing was excessive, resulting in an abnormally low knee flexion velocity at toe-off.

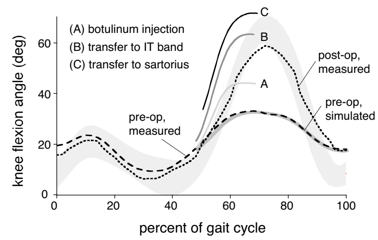

Figure 1. Knee flexion trajectories following simulated treatments. The subject's measured knee angles before and after surgery are shown for comparison. Shaded area is the normal mean ± 1SD.

Decreasing the excessive excitation of rectus femoris, simulating the effects of botulinum toxin injection, increased knee flexion by about 10º (Fig. 1, A). Eliminating the excessive knee extension moment of rectus femoris while leaving the hip moment intact, simulating a surgical transfer of the rectus femoris insertion to a site lateral (Fig. 1, B) or posterior (Fig. 1, C) to the knee, increased the peak knee flexion by about 30º. A substantial improvement was achieved regardless of whether the muscle was converted to a knee flexor. The simulated improvements were similar to the subject's actual improvements after tendon transfer surgery.

CHALLENGES

Simulation-based analyses of muscle function during walking provide insights not available from experimental methods alone [e.g., 2]. Before simulations can be widely used to guide treatment decisions for individual patients, however, advancements in the following areas are needed:

- Experimental data that more accurately describe patients' joint axes, trunk motions, and foot-floor interactions during consecutive strides.
- Models that more accurately and efficiently characterize patients' musculoskeletal geometry and joint kinematics.
- Muscle-tendon models that characterize the effects of pathology, surgery, and other treatments on the time course of muscle force generation.
- Methods for analyzing and validating simulations that better elucidate the actions of muscles and the consequences of neuromusculoskeletal impairments.
- Techniques for incorporating representations of sensory-motor control into simulations of normal and abnormal gait.
- Clinical studies that test whether subject-specific dynamic simulations can improve treatment outcomes.

REFERENCES

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