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SYNTHESIS OF SUBJECT-SPECIFIC TASK-LEVEL MOTIONS FOR PREDICTIVE SIMULATIONS OF BALANCE RECOVERY

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INTRODUCTION

Among older adults in the U.S., falls are the leading cause of nonfatal injuries, with 2.5 million treated in 2013 alone [1], at a direct healthcare cost of 30-billion dollars annually [2]. The number of fall events continues to rise each year, providing a rationale to study balance control and how it relates to a fall event. Through this approach prophylactic exercise prescriptions can be developed, to reduce the number of preventable falls. Experiments have identified many aspects of falls; however, simulations can complement experiments to help uncover mechanisms of coordinated and uncoordinated movements for predicting balance recovery. Synthesis of subject-specific movements requires accurate musculoskeletal modeling, complex dynamic simulation, and robust control system design. Human movement involves closed-loop control and a combination of biomechanics and robotics approaches offers great potential for improving fall-related interventions; in addition, it will accelerate the study of human movement control and subject-specific outcome prediction.

METHODS

Motion capture and electromyography (EMG) data (Gluteus Maximus, Gluteus Medius, Rectus Femoris, Vastus Medialis & Lateralis, Biceps Femoris, Semitendinosus, and Medial Gastrocnemius) of balance recovery were collected from a healthy female (height 1.72 m; mass 68 kg) and male (height 1.79 m; mass 84.5 kg) using a Computer Assisted Rehabilitation Environment (CAREN) system (Fig. 1). The CAREN base was randomly (1 to 3 sec into trial) translated (6 cm) anterior or posterior at maximum viable speed (40 cm/s), while each subject stood on one foot lifting the contralateral foot (>10 cm) above the surface.

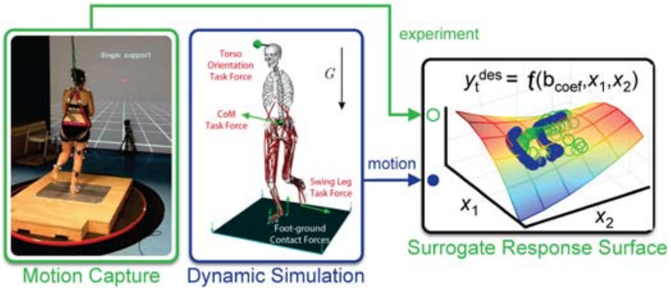

Figure 1: Subject-specific surrogate models created from experimental motion capture data and used for desired task-level coordination during simulations.

Subject-specific dynamic simulations with supporting contacts were created from a three-dimensional, full-body musculoskeletal model with 17 degrees of freedom and 92 muscle–tendon actuators using OpenSim [3] and a custom MATLAB S-function [4]. The simulated motion was combined with surrogate models of experimental motion capture data to begin forming the closed-loop control (Fig. 1; Fig. 2 top right). Separate quadratic response surfaces were developed for each desired subtask (e.g., swing foot position) as a function of a primary task (e.g., center of mass position) to approximate subject-specific task-level movement coordination allowing synthesis of a range of motions (e.g., prediction of post-treatment outcome from pre-treatment motion).

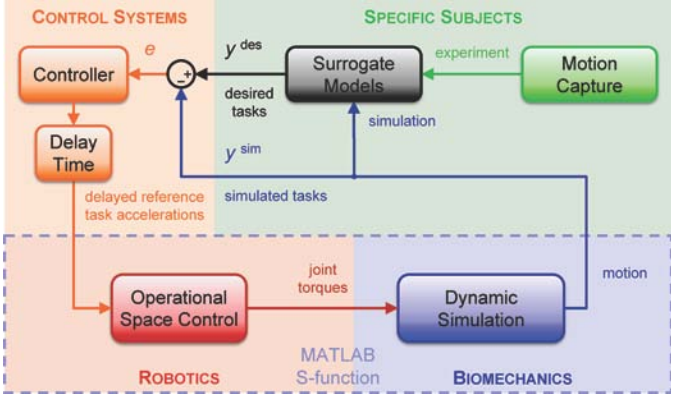

Figure 2: Overview of task-level simulation using OpenSim and MATLAB.

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Differences between simulated and desired tasks were used to compute task errors (Fig. 2 top left). Differences between simulated and experimental tasks were minimized by tuning proportional-integral-derivative (PID) controller gains in the feedback loop to a specific subject. Desired task accelerations were delayed (60 ms) to represent time lags for neuromechanical processes.

Task accelerations were used to synthesize whole-body motions using prioritized, multi-task approaches for a support-consistent formulation maintaining the foot-ground contact [5, 6] (Fig. 2 bottom left). Each task force is comprised of the task acceleration multiplied with its task space inertia matrix, plus velocity and gravity compensation terms. Composite joint torques to simultaneously control all tasks are found by multiplying task forces by their respective reduced Jacobians and dynamically-consistent, priority-level-determined, null space matrices for each task.

Joint torques from the prioritized operational space motion control were used for a musculoskeletal dynamic simulation with supporting contacts (Fig. bottom right). Static optimization minimized the sum of muscle activations squared subject to bounds (0 to 1) and constraints on net muscle moments, the product of muscles forces and their moment arms, equaling the total joint torques for the tasks.

The synthesized motions were compared with the experimental ones from each subject. In addition, the model's muscle activations were compared with processed experimental EMG from each subject.

RESULTS AND DISCUSSION

The synthesized motions and muscle activations reproduced the balance recovery experiments. The simulated whole-body center of mass displacements were, on average, within 0.7 cm (female) and 1.3 cm (male) of experimental ones (Fig. 3a male subject). Model muscle activations (Fig. 3b bottom row) matched experimental EMG (Fig. 3b top row) in timing of peak muscle excitations. Differences between simulated and experimental balance recovery were similar in both anterior and posterior translation directions of the CAREN base.

The combination of biomechanics and robotics approaches for closed-loop control simulations allowed synthesis of subject-specific task-level motions. The surrogate response surfaces allowed synthesis of new, coordinated motions without additional experimental motion capture data. The optimal PID gains allowed control over simulated tasks for each subject. The operational space control allowed multiple prioritized tasks to balance on a single supporting limb in contact with the ground. The four areas of the closed loop (Fig. 2: specific subjects, control systems, robotics, and biomechanics) offer numerous directions for future work to advance the study of human balance control and subject-specific outcome predictions.

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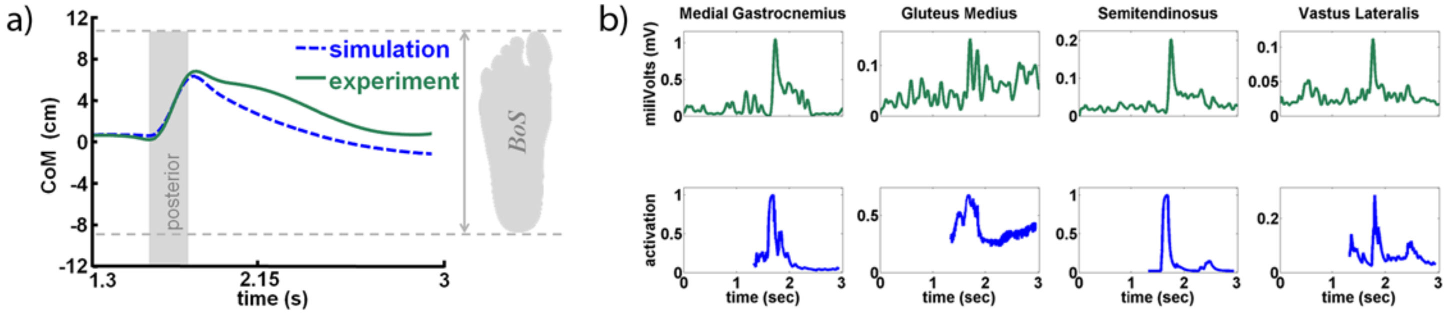

Figure 3: Center of mass displacement for one male subject in the anterior-posterior direction (a) and muscle activities for four selected muscles (b) from the balance recovery experiment (green) and simulation (blue).