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DYNAMIC SIMULATION OF UPPER LIMB MOVEMENT IN TWO SOFTWARE PLATFORMS

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INTRODUCTION

There are several opensource or commercially available software platforms widely used for the development of dynamic simulations of movement. While computational approaches to calculating the dynamics of a musculoskeletal model are conceptually similar across platforms, differences in implementation may influence simulation output. To understand predictions made using simulation, it is important to understand differences that may result from the choice of model or platform. Our aims were to 1) develop a musculoskeletal model of the upper limb suitable for dynamic simulation and 2) evaluate the influence of the choice between SIMM-SD/Fast and OpenSim simulation platforms on gravity- and EMG-driven simulations of movement.

METHODS

We developed a dynamic model of the shoulder, elbow, forearm, and wrist using a previously developed kinematic model of the upper limb [1] as a foundation. The dynamic model includes 7 degrees of freedom at the glenohumeral joint, elbow, forearm, and wrist with conventions as recommended by ISB [2] and constrained movement of the scapula and clavicle [3]. Appropriate inertial properties were defined for the hand, humerus, radius, ulna, clavicle, and scapula [4, 5]. Fifty Hill-type muscle-tendon actuators representing 32 muscles and muscle compartments were included. Optimal fiber lengths, pennation angles, and tendon slack lengths were as described by Holzbaur et al. [1]. Peak isometric muscle forces in the model were determined from previously published muscle volume and isometric joint strength data determined for these muscles and joints in healthy young adults [6, 7].

We implemented this model for simulation in both the SIMM-SD/Fast (SIMM 6.0, SD/Fast B.2.8) [8] and OpenSim (2.4) [9] environments. We performed simulations of isolated shoulder, elbow, and wrist movements using several approaches to evaluate the influence of specific known differences between platforms. In particular, we focused on three important features of a dynamic simulation that are calculated differently in the two environments: joint restraint torques and damping, muscle moment arms, and muscle force.

We performed a series of EMG-driven dynamic simulations of single-joint shoulder, elbow, and wrist movements. EMG was obtained experimentally from 9 muscles crossing the shoulder, elbow, and wrist using 1 cm surface electrodes. Five trials of isolated (i) shoulder abduction, (ii) elbow flexion, and (iii) wrist flexion were each performed by a single subject. Only the degree of freedom of interest was free to move in the experiments and corresponding simulations. EMG recordings were filtered, rectified, and normalized to the appropriate MVC. Processed EMG data from each trial were applied as muscle excitations driving a forward dynamic simulation in each platform. Kinematic results were compared between platforms and to kinematic data recorded during each trial.

We evaluated the differences observed between the EMG-driven simulation results in the context of modeling platform by comparing forward dynamic simulations without muscle excitations. Specifically, we performed gravity-driven, forward dynamics simulations (i) without muscles to evaluate the effects of different implementations of restraint torques and damping; and (ii) with passive muscles to focus on the influence of differences in the models of muscle path and force-generation. Joint restraint functions define forces or torques applied to the generalized coordinates in order to restrain them from going outside their defined ranges of motion. In both environments, we used the provided toolboxes to define the previously reported elastic and velocity-dependent (i.e., damping) joint restraint torques at the shoulder and elbow [10] and at the wrist [11]. The elastic torques could not be implemented identically because the parameterization available to users differs in the two platforms. In addition, joint damping is implemented throughout the range of motion in the SIMM-SD/Fast environment, but only at the limits of joint ranges of motion in OpenSim. The method for calculating moment arms for muscles with moving muscle points and the algorithm for calculating muscle force given the muscle model described by Schutte [12] also differs between platforms in these versions of the software.

RESULTS

Overall, EMG-driven forward dynamic simulations indicate that the dynamic model of the upper limb developed in this study predicts similar kinematic motion when the same EMG data are used in two popular modeling platforms. For example, when surface EMG data from the major wrist flexors and extensors served as inputs, the simulated wrist kinematics resulting from SIMM-SD/Fast were comparable to those resulting from OpenSim (c.f., Fig. 1, red and blue curves; RMSE=12.5°). Both sets of simulation results reasonably approximated the measured kinematics (c.f., green curve, Fig. 1). These simulations took substantially longer to complete in SIMM (2hrs:11min:11s) than in OpenSim (0hrs:03min:46s). Similar results were also observed at the elbow (RMSE=12.6°; SIMM: 2:55:30, OpenSim: 0:09:06) and shoulder (RMSE=6.1°; SIMM: 10:37:24, OpenSim: 0:43:00). The largest differences we observed between platforms occurred at the end of the movement, when muscles were minimally active (c.f., Fig. 1, shaded region; RMSE=8.2° when active vs. 23.0° when resting).

Results from the gravity-driven simulations highlighted joint damping as a feature that critically influences simulated kinematics. In the absence of muscle forces, the wrist reaches the equilibrium posture more slowly and with less oscillation than the same simulation in OpenSim because damping is applied throughout the range of motion in SIMM (Fig. 2). When the gravity-driven simulations include passive muscle forces, the effect of the different damping implementations is more pronounced (Fig. 3). In addition, the equilibrium postures of the wrist are the same between platforms when muscles are excluded from the simulations (Fig. 2), but are shifted by ~20° when passive muscle forces are included (Fig. 3).

DISCUSSION

We successfully implemented a dynamic model of the upper limb including the shoulder, elbow, wrist, and muscles crossing these joints. Simulations completed in OpenSim were notably faster in all cases. Our simulations show that differences between the SIMM-SD/Fast and OpenSim platforms can influence simulation outcomes but our analyses suggest that the most substantial divergence in results occurs in the absence of active muscle forces. While subtle, these differences may have important implications for upper limb simulations, in which forces and inertial properties are smaller compared to the lower limb. In addition, the weakened or paralyzed upper limb, can involve very small active forces or passive forces only. In these cases, especially, the differences we document here are important to recognize.

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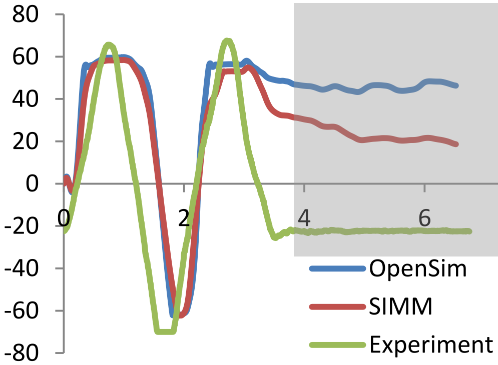

Figure 1. EMG-driven wrist flexion in SIMM, OpenSim, and recorded kinematics. Shaded region indicates limited muscle activation.

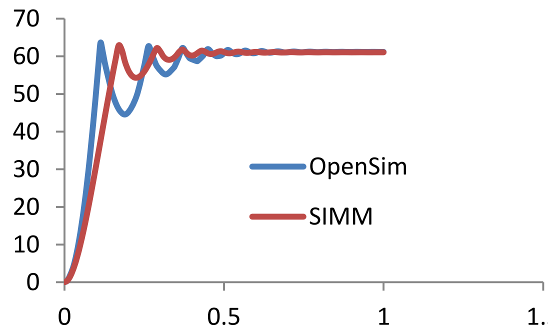

Figure 2. Wrist flexion against gravity in the absence of muscles in SIMM and OpenSim.

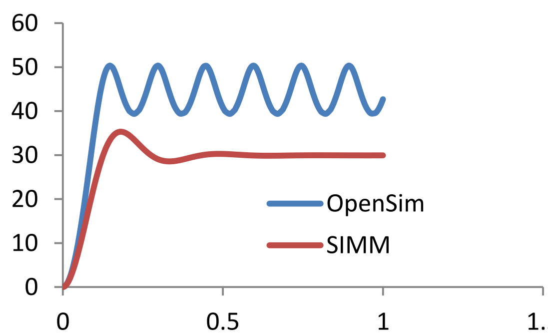

Figure 3. Wrist flexion against gravity with passive muscles in SIMM and OpenSim.

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