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REAL-TIME SIMULATION OF THREE-DIMENSIONAL SHOULDER GIRDLE AND ARM DYNAMICS

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SUMMARY

The aim of this study was to develop and evaluate a musculoskeletal model of the upper limb that is able to simulate the dynamics of the arm and shoulder girdle in real time. Results show that the model was able to realistically simulate an elevation of the arm of 1.3s duration in 1.2s, given a predetermined set of neural inputs. Maximum isometric moments predicted by the model largely agree with those reported in the literature. Integrated with a visualization environment, the model will form the basis of a *dynamic arm simulator*. This will facilitate the development and testing of advanced neuroprostheses for the restoration of function in neuromuscular disorders such as high-level spinal cord injury and stroke.

INTRODUCTION

Musculoskeletal models can be used to accelerate the development of novel rehabilitation interventions and assistive devices. In particular, we have recently described an application of a forward dynamic (FD) model for evaluation of a brain-computer interface. The model simulated planar control of a paralysed arm reanimated by functional electrical stimulation [1]. In order to extend that control to functional, whole arm movement in 3D, it is necessary to simulate the motions of the scapula and clavicle as well as the arm in the model.

Blana *et al*. have previously described a comprehensive model of the shoulder and upper limb [2], implemented in SIMM. Real-time simulation with that model would provide a suitable platform for assessing artificial control of 3D shoulder and arm movement. However, FD simulations involving complex models of the musculo-skeletal system are typically slow, due to the stiff nature of the system dynamics requiring very small integration time-steps and the computation time for calculating muscle paths.

The goal of this study was therefore to adapt a complex, 3D musculoskeletal model of the whole arm and shoulder girdle to run in real time, using the efficient methods described in [3]. Here we give an overview of the model and evaluate its performance in terms of simulation speed and the reliability of predicted maximum isometric moments.

METHODS

The model, comprising 7 body segments, 11 degrees of freedom and 138 muscle parts, was initially built in SIMM, and based on the anatomical model parameters of the Delft Shoulder and Elbow Model, or DSEM [4,5]. The model was converted to OpenSim, which was used to calculate muscle moment arms for a large number of arm positions. Based on these, polynomial regression models were generated for the muscle paths, which are much faster to compute than exact moment arms. A Hill-type muscle model was used to describe muscle activation and contraction dynamics [3].

Combining the equations of motion with muscle dynamics, the model can be described with an implicit, first-order differential equation. All functions in the model are continuous, allowing analytical expression of the system derivatives. This enabled efficient simulation with a first-order Rosenbrock formula [3], using a step-size of 4ms.

Glenohumeral (GH) joint stability is monitored in real time by summing all the muscle forces crossing the GH joint and calculating the joint reaction force vector relative to the rim of the glenoid. Scapulo-thoracic contact was modelled as deformable, rather than a kinematic constraint as is typically used in inverse-dynamic models. Stiffness is high when a point on the scapula goes inside the ellipsoid, and zero (or low) when the point is outside the ellipsoid. This allows a winging scapula to be simulated by the model.

Model performance was evaluated by two means. The first was a simple forward-dynamic simulation of arm flexion using a fixed set of neural inputs. This was used to assess the simulation speed of the model and its ability to produce a standard movement. The second test was to compare the model-predicted maximum isometric joint moments in a number of positions with values reported in the literature.

The set of neural inputs used to generate forward flexion of the arm was taken from an inverse-dynamic simulation using the DSEM. The input motion used to generate the neural excitation set was averaged from measured motions taken from approximately 20 subjects. Neural inputs were estimated every 50ms throughout the movement.

To evaluate the strength performance of the model, an optimization was carried out whereby a series of fixed arm positions were specified and the neural commands required to achieve maximum moments were calculated, subject to the following constraints: GH stability was maintained by ensuring that the joint reaction vector pointed inside the glenoid; and scapular winging was prevented by requiring the scapular points Trigonum Spinae and Angulus Inferior to remain in contact with the thorax. The orientations of the scapula and clavicle were not specified during this optimization, but were solved by the model while maximizing the joint moments.

RESULTS AND DISCUSSION

Model simulation speed was tested on a 2.67GHz Intel i5. The simulated movement duration was 1.3s, and using a 4ms time-step the simulation was completed in 1.2s, allowing faster than real time simulation.

The arm start and end positions resulting from the forward-dynamic simulation are shown in Fig. 1. The motion of the arm was elevation from approximately 10°-80°, in a plane 60°-80° from the frontal. The inset shows the intersection of the GH reaction force vector and the glenoid; it can be seen that GH stability is maintained throughout the movement.

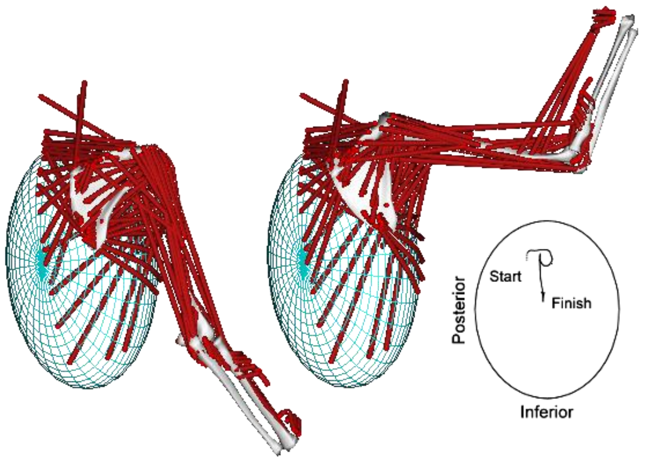

Figure 1 The initial and final positions of the arm, and position of the joint reaction force (inset), during simulated elevation.

Fig. 2 shows the comparison of model-predicted maximum isometric moments to those reported in the literature. There is general agreement between the model-predicted moments and those from the literature, both in the shape of the torque-angle curves, and in the magnitudes of the maximum moments reported. However, some differences are seen, and these are discussed below.

For elevation of the arm (Fig. 2A), scapular abduction moments agreed well with the experimental data throughout the range of motion, with a peak of about 80Nm and a slight decrease in moment with increasing elevation angle. For scapular adduction moments, however, the model values were higher than those found in the literature, reaching over 100Nm at 90° elevation. In addition, the model predicted increasing strength up to 90° of abduction, while the experimental data from Garner [6] show a slight decrease at angles above 70°.

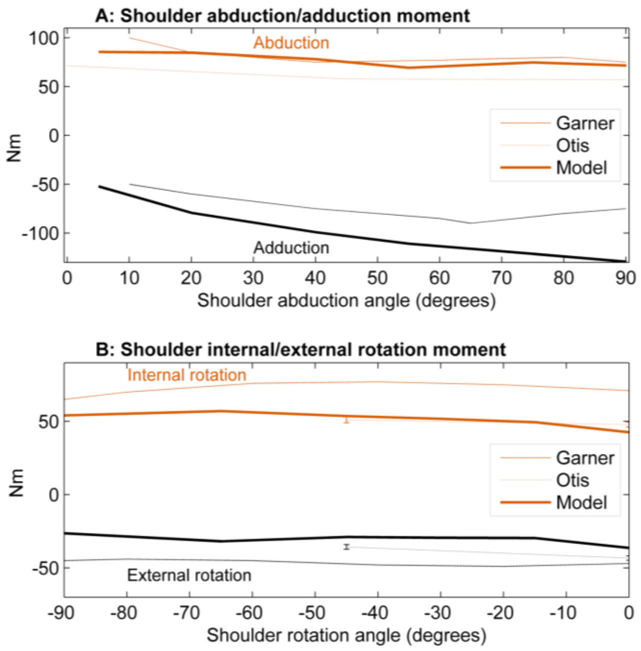

Figure 2 Model-predicted shoulder ab/adduction (A) and rotation (B) moments compared to those from the literature.

For shoulder internal rotation moments (Fig. 2B), the model data show the same shape as the experimental data with the maximum torques decreasing slightly at both ends of the range of motion. The values agree very well with those of Otis [7], but are significantly lower than those found by Garner. It should be noted that the model data are taken from a single cadaver source and not scaled in any way, so we might expect significant deviation from values in other small populations. During external rotation, the model also exhibits qualitatively feasible behaviour, with relatively constant values through the range of motion, but produces somewhat lower torques than those found in the literature.

The scapulo-thoracic constraint requires that the medial border of the scapula stays a fixed distance away from the thorax, which may not be true for all shoulder positions. The rigidity of this constraint may therefore be a significant factor affecting the model-predicted shoulder kinematics and hence the maximum moments generated.

CONCLUSIONS

The simulation results shown demonstrate that our model runs comfortably in real time on normal desktop hardware and reliably simulates the moment-generating behaviour of a real human arm under a range of conditions. We expect this to form the basis of a valuable platform for the development and testing of advanced neuroprostheses for the upper limb.

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