AN EMG-DRIVEN BIOMECHANICAL MODEL OF THE ELBOW

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INTRODUCTION

Modelling and simulation of musculoskeletal movement has potential for application to the prediction of functional movement from functional electrical stimulation, orthopaedic surgery, and the prosthetic limbs.

The estimation of muscle force from surface electromyographic (sEMG) signals has been a significant biomechanical challenge. The muscle force estimation involves: i) properly characterizing the dynamic behaviour of muscle and incorporating it into a mathematical model driven by sEMG data, and ii) experimentally validation of the simulation model.

VALIDATION EXPERIMENT

To functionally validate the computational muscle model, it was necessary to identify a relatively simple anatomical joint actuated with relatively few uniarticular muscles. Our ability to identify the accuracy of the muscle model is reduced once multiple muscles are required as well as if these muscles would have a bi-articular function. To satisfy our needs, the elbow joint was chosen for its planar operation as well as the action of the muscles surrounding it.

Elbow flexion-extension was chosen as a task to both record and model. A rehabilitation dynamometer (Biodex II, Biodex Corp. Shirley, NY) allowed for restriction of limb movement to achieve 14 testing conditions:

- isokinetic @ 30 / 90 / 180 / 300 deg/sec
- isotonic @ 13.56 / 27.12 / 54.23 N.m
- eccentric (54.23 N.m) @ 30 / 60 / 120 deg/sec
- isometric @ 0 / -45 / -90 deg

Six volunteer able-bodied male subjects maximally flexed and extended there elbow through the complete range-of-motion for 10 seconds while the dynamometer modulated the resistance and mode of contraction. Three trials of each condition were performed. (see Figure 1).

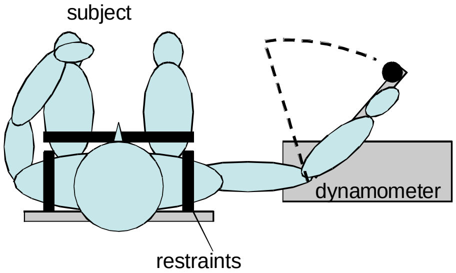

Figure 1: Experimental setup (top view)

EMG signals (rectified, low-pass filtered @ 15Hz) of six muscles were recorded at 500Hz: biceps brachii, brachialis, brachioradialis, and triceps brachii (medial, intermediate, and lateral heads). At the same time, dynamometer data was recorded: joint angle, angular velocity, and joint moment at 500Hz.

A maximal concentric isokinetic trial @ 30 deg/sec for 20 seconds was used as a basis to normalize the EMG signals.

MODEL

A generic computational lumped-parameter Hill-type muscle-model, based on the work of Zajac [1] and other [2][3], was created in Simulink (see Figure 2) incorporating various geometric, dynamic (active and passive), and electromyographic properties of muscle fibre and tendon:

- series-elastic element (tendon modelling)
- parallel-elastic element (passive muscle stiffness)
- active element (active muscle contraction)
- force-length relationship
- force-velocity relationship
- muscle fibre pennation angle
- optimal fibre length
- optimal fibre length/activation relationship
- tendon slack length
- electromechanical delay
- maximum isometric muscle force
- EMG gain
- EMG-activation transformation shape

A 6-muscle computational musculoskeletal model of the human elbow was developed in Simulink

(Mathworks Inc.). The model consisted of the biceps brachii, brachialis, brachioradialis, and triceps brachii (medial, intermediate, and lateral heads). Additionally, it was necessary to model the moment-of-inertia for the motor/interface and each muscle's musculotendon length and moment arm was defined as a function of elbow flexion angle from published data [4].

Figure 2: muscle model in simulink

Each muscle-model was driven using the initial conditions (recorded dynamometer joint angle) and the rectified-averaged surface EMG of the 6 recorded muscles. To configure each muscle model, some muscle specific parameters were required (tendon-slack length, optimal muscle-fibre length, maximum isometric muscle force). Other parameter values for the muscle model were considered common to all muscles. Various muscle parameters were muscle specific. Three repetitions of fourteen different types of maximal elbow flexion-extension exercises were recorded covering isokinetic, isotonic, isometric, and eccentric muscle contractions at various levels and orientations.

OPTIMIZATION

We have chosen to compare the time-varying joint moment profile of the simulation model to that of the recorded data from the dynamometer. The simulated joint moment is a summation of the computed muscle moments and the inertial moment. (Figure 3).

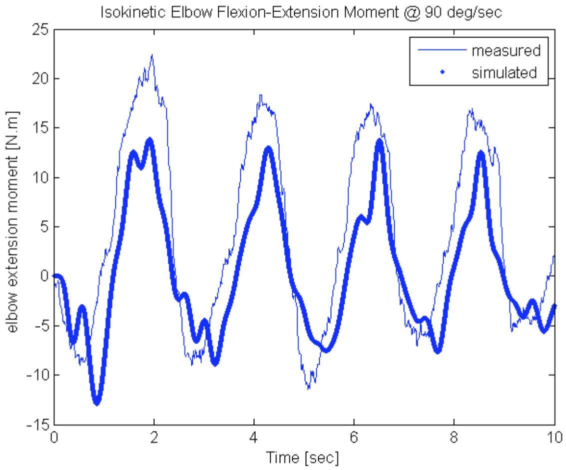

Figure 3: Measured vs. Simulated Joint Moments

The application of numerical optimization to the model was to define a set of common muscle parameters that would be satisfactory to achieve similar results between the simulated and recorded elbow joint moments. The DIRECT (division of rectangles)[4] numerical optimization algorithm (a global search routine) was used to minimize the RMS error between the measured and simulated elbow joint-moments. The optimization was performed for each subject for each of the fourteen modes of muscle contraction. One-hundred iterations of the DIRECT algorithm were performed for each simulation set.

RESULTS

The identification of a single generalizable set of muscle parameters suitable for all muscles for all situations for an individual was determined to be unrealistic. The results are too numerous to exhibit in this paper, put general observations can be made. Many optimized parameter values were constant across subjects but differed across the contraction type and level. Other optimized parameter values differed between subjects. From these results, not a single, but a reduced number of parameter sets were adequate to cover the range of contraction types.

For purposes of establishing a general level of accuracy, a single optimized parameter set identified for each subject to cover all trials/conditions performed. Model estimates of net joint moments compared to experimentally measured moments across the 14 experimental conditions indicated a strong mean correlation across all trials for all subjects (r = 0.83) with an acceptable joint moment error

(*RMSE* = 20.06%). As mentioned earlier, the compromised parameter set resulted in the elbow model's predictive performance varying across the modes of contraction.

The validation results from the elbow muscle, integrating the muscle models demonstrate that driving input from surface EMG only is capable of achieving accurate dynamic predictions of muscle forces/moments. These results bode well for application to various outcome assessments.

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