DETERMINATION OF SUBJECT-SPECIFIC MECHANICAL PROPERTIES OF INDIVIDUAL ANKLE JOINT MUSCLES

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INTRODUCTION

The mechanical properties of human muscles govern their force response to neural commands, and thus have a profound effect on human movement. Due to redundancy in the human muscular system, the mechanical properties of individual muscles are difficult to measure in vivo, with direct measurement possible only with highly invasive techniques (Komi et al. 1987). While such methods produce accurate data, they can only be applied to animal models or in rare human cases. A less invasive method is to collect data on the properties of whole joints and use modeling and optimization techniques to estimate individual muscle properties (Caldwell & Chapman, 1991; Garner & Pandy 2003). With this approach, subject-specific measures are combined with data from the literature to compute muscular properties. Of importance is the need to use as many subject-specific measures as possible, because muscle mechanical properties change with training, disuse, aging, and disease.

Therefore, the purpose of this study was to develop a method that integrates joint and muscle measurements with modeling and optimization techniques to estimate the subject-specific mechanical properties of individual muscles controlling the ankle joint.

METHODS AND PROCEDURES

Dynamometer Experiments
Three male subjects (27-29 yrs) produced maximal effort dorsi- and plantarflexor torque sequences across a range of isometric ankle angles and isovelocity angular velocities. EMG was recorded from the tibialis anterior (TA), gastrocnemius (GA), and soleus (SO) muscles. From these trials subject-specific isometric torque-angle ($T\theta$) and dynamic torque-angular velocity ($T\omega$) relations were determined (Caldwell & Chapman, 1991).

Muscle Imaging
For each subject, TA, GA, and SO muscle volumes were computed from cross-sectional areas measured from serial axial magnetic resonance images (MRI) of the entire leg. Physiological cross-sectional areas (PCSA) were estimated by dividing the volumes by fiber lengths reported in the literature. Ultrasound imaging was used to assess internal muscle elasticity during 30 s ramped isometric dorsi- and plantarflexion trials. Displacements of points on the deep muscle aponeuroses were plotted against measured ankle torque to create torque-extension ($T\Delta L$) relations for ankle dorsi- and plantarflexion.

Modeling, Simulation, and Optimization
A musculoskeletal model of the ankle joint was used to simulate the dynamometer experiments. Muscle dynamics were represented by two-component models (Hill 1938), consisting of contractile (CC) and series elastic (SEC) components. CC behaviour was characterized by force-length (FL) and force-velocity (FV) relations, while the SEC compliance was represented by a nonlinear force-extension (F\Delta L) relationship.

First, model FL and F\Delta L parameters were optimized through isometric simulations that tried to match the experimental $T\theta$ and $T\Delta L$ relations, with GA and SO relative force capabilities constrained by their PCSA sizes. CC FV parameters were then optimized in isovelocity simulations that tried to replicate the experimental $T\omega$ relations, with model kinematics and excitation onset times based on dynamometer and EMG data, respectively.
RESULTS AND DISCUSSION

The root-mean-squared error between the optimized model and experimental Tθ and Tω data averaged 0.63 ± 0.47 Nm (Mean ± SD). For all subjects, the only area where the model and experimental data did not closely match was for eccentric dorsiflexion (Fig. 1). This may be because there were more concentric data points available, biasing the optimization. Plantarflexor Tω data matched better because there were twice as many free muscle parameters to optimize.

Figure 1. Experimental (red) and model (blue) Tθ and Tω curves for Subject 3 (S3). (+θ DF)

Optimized muscle properties are shown for one subject in Fig. 2. On average, the extension of the TA FΔL at P₀ (7.5%) was larger than the GA (6.7%) and SO (6.9%). The FL parabola was narrowest for TA (0.77-1.23 L₀), and wider for the GA (0.75-1.25 L₀) and SO (0.72-1.28 L₀). Coefficients [a/P₀, b/L₀] defining the FV relation averaged [0.1, 0.58] for TA, [0.5, 2.0] for GA, and [0.55, 0.3] for SO. Optimized P₀ values (Table 1) were lower than Gerritsen et al. (1998), who reported values of 1528 N for TA, 1639 N for medial GA only, and 3883 N for SO.

This methodology has improved upon that described in Garner & Pandy (2003) by including subject-specific data from MRI and ultrasound imaging, and concentric and eccentric isovelocity dynamometer data. We are currently refining the methods in studies examining changes in muscle mechanical properties that occur with age.

Table 1. Optimized model P₀ values and estimated PCSAs from MRI volume data.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Property</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
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<td>TA</td>
<td>P₀ (N)</td>
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<td>PCSA (cm²)</td>
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<tr>
<td>PCSA (cm²)</td>
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<td></td>
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<tr>
<td>SO</td>
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<td>2334</td>
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<tr>
<td>PCSA (cm²)</td>
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<td>148</td>
<td>137</td>
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Figure 2. Optimized model properties of the ankle joint muscles for Subject 3 (S3)

REFERENCES


ACKNOWLEDGEMENTS

Supported by NRSA 1F31EB005073 (CJH) and NIH R03AG026281 (GEC).