A 3D MODEL OF MUSCLE REVEALS THE CAUSES OF NONUNIFORM STRAINS IN THE BICEPS BRACHII

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INTRODUCTION
Biomechanical models generally assume that muscle fascicles shorten uniformly. However, dynamic magnetic resonance (MR) images of the biceps brachii have recently shown nonuniform shortening along some muscle fascicles during low-load elbow flexion (Pappas et al., 2002.)

The purpose of this study was to uncover the features of the biceps brachii muscle’s architecture and material properties that could cause the nonuniform shortening. To do this, we created a finite-element (FE) model of the biceps brachii and compared the tissue strains predicted by the model with dynamic MR data. We then used the model to explore the effects of the muscle’s internal geometry and material properties on the strain distributions.

METHODS
We modeled muscle as a transversely isotropic, quasi-incompressible, hyperelastic material based on the model described by Weiss et al. (1996). In our model, the strain-energy function (W) was described by:
\[
W = F_1(l, \text{act}) + F_2(j) + F_3(b) + F_4(q),
\]
where \(l\), \(q\), and \(\text{act}\) represent the fiber stretch, volume stretch, and activation level, respectively. The along-fiber shear strain (\(j\)) and the cross-fiber shear strain (\(b\)) were derived from a physically-based strain invariant set for transverse isotropy proposed by Criscione et al. (2001). We defined \(F_1\) to be consistent with the nominal force-length characteristic of a muscle fiber, scaled by the activation level (Zajac, 1989).

\(F_2\) provides the shear stress-strain relationship in the along-fiber direction, and \(F_3\) provides the shear stress-strain relationship in the cross-fiber direction. \(F_4\) was defined such that tissue was nearly incompressible. The 2\textsuperscript{nd} Piola-Kirchhoff stress was determined by \(\partial W/\partial E\), where \(E\) is the Green-Lagrange strain.

The finite-element brick mesh geometry represented the long head of the biceps muscle tissue and aponeuroses (Fig. 1A) and was axially symmetric about the centerline, creating a three-dimensional muscle model. A map for fiber directions (Fig. 1B) was created based on fascicle arrangement and aponeurosis dimensions measured from static MR and ultrasound images (Asakawa et al., 2002) and used to define the fiber direction for each element.

Figure 1: Sagittal-plane geometry of the FE mesh (A) and the fiber map (B).

We used NIKE3D, a nonlinear finite-element code (Puso et al., 2002), to generate simulations of the biceps muscle at 15\% activation during a quasi-static 4cm length change. We compared the strains in the model to dynamic MR data (Pappas et al. 2002). These data describe the displacements of 1-cm regions in the biceps during elbow flexion in 12 subjects. To compare these data, we calculated average change in length along 1cm regions in the FE model.
RESULTS AND DISCUSSION
The finite-element model predicted changes in length (or “strains”) along both the anterior and centerline regions that were within one standard deviation of the average changes in length measured in 12 subjects (Fig. 2). The strains were not uniform along the centerline fascicles (Fig 2A); the greatest strains occurred at the proximal end of the muscle. The strains along the anterior fascicles (Fig. 2B) were more uniform than the strains along centerline fascicles. Analysis of the model showed that the difference in lengths between the centerline and anterior fascicles was the primary cause of the nonuniform strain along the centerline fascicles. The presence of the distal aponeurosis also affected the strain distributions. Because of the aponeurosis, the centerline fascicles insert 6cm proximal to where the anterior fascicles insert. This "staggering" of the fascicles, coupled with the along-fiber shear stiffness, resulted in nonuniform strain along the fascicles. The nonuniform strains in the biceps model are strongly influenced by the muscle-tendon architecture, suggesting that the degree nonuniform shortening will vary across muscles of various architectures. Continuum representations of muscle, combined with in vivo image data, are needed to deepen our understanding of how complex geometric arrangements of muscle fibers affect muscle force production.

REFERENCES

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