SCALING OF MUSCLE VOLUMES IN THE UPPER EXTREMITY

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INTRODUCTION

Humans vary greatly in size and shape, yet biomechanists often use generic musculoskeletal models with average parameters to examine questions of muscle function and coordination. While this approach allows researchers to investigate general principles underlying human movement, it is unclear how conclusions derived from studies of generic models apply to individuals of different sizes.

Muscle force-generating properties used in musculoskeletal models are often derived from cadaveric studies of muscle architecture. This could complicate scaling of generic models for two reasons. First, cadaveric specimens may not accurately reflect the absolute or relative sizes of muscles in young, healthy subjects. Second, cadaveric studies of muscle architecture often focus on individual muscle groups; this is especially true for the upper limb, where muscle parameters have been quantified separately for the shoulder [1], elbow [4], and forearm [2,3]. This study addresses both issues in the upper extremity by i) measuring volumes for all muscles of the upper limb in young, healthy subjects using magnetic resonance imaging, and ii) comparing these data to the different sources available in the literature.

METHODS

Five subjects (4 females, 1 male, 24-37 years) with no injury or pathology of the upper limb were studied. All subjects provided informed consent. Each subject was imaged supine in a 1.5T MRI scanner (GE Healthcare, Milwaukee, WI). Axial images were acquired from shoulder to wrist using a 3D spoiled gradient echo sequence with 3 mm sections. Shoulder images were obtained with the body coil with TE = 3 ms, TR = 11.6 ms, flip angle (FA) = 30°, matrix = 512x192, and field of view (FOV) = 32 cm. Elbow and forearm images were acquired using a flexed array long bone coil (Medical Advances, Milwaukee, WI) with TE = 5 ms, TR = 23 ms, FA = 45°, matrix = 320x192, and FOV = 16 cm.

To calculate muscle volume, we reconstructed the three-dimensional geometry of the upper limb muscles. Muscle boundaries were segmented in the axial images and a three-dimensional polygonal surface was created for each muscle from the outlines (3D-Doctor, Able Software Corp., Lexington, MA). Muscle volumes were then normalized by the corresponding volume reported in the literature [1-4] to produce a "scaling ratio". For a given muscle, a ratio greater than 1 indicates that its volume is larger than the cadaver data. To determine if muscle volumes obtained from the different literature sources represent the relative proportion of muscle volumes for a single individual, we compared scaling ratios across upper limb segments for each subject.

RESULTS AND DISCUSSION

The ratios between the volumes measured in this study and the volumes from cadaveric data ranged from 0.91 to 3.73. While scaling ratios varied across subjects, all muscles scaled by approximately the same ratio for each subject. For example, the scaling ratios for deltoid, a shoulder muscle, and extensor carpi radialis brevis (ECRB), a forearm muscle, were approximately equal (Fig. 1, red squares). Similarly, the ratios for brachioradialis, an elbow muscle, and pronator quadratus (PQ), a forearm muscle, were comparable (Fig. 1, blue triangles).

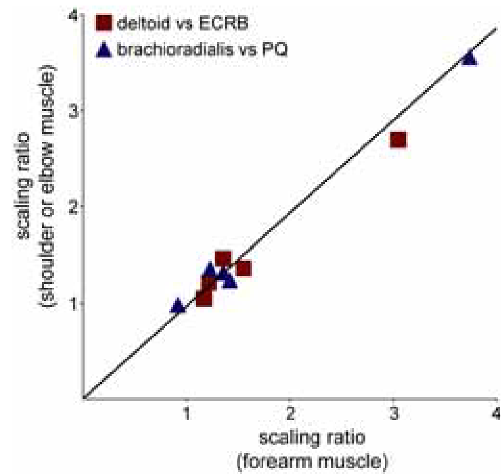

Figure 1: Scaling ratios for example proximal muscles vs. forearm muscles.

Muscle volumes reported in cadaveric studies are equivalent to the volumes measured in the females in this study (height ranged from 157 to 165 cm). The one male subject evaluated here (height = 175 cm) had substantially larger muscle volumes. Data from different architecture studies scaled uniformly to muscle volume for a given subject. That is, when scaling ratios for shoulder or elbow muscles were plotted against ratios for forearm muscles, all points fell close to a line with slope equal to one. This is encouraging for researchers who must combine data sets from multiple studies to estimate force-generating properties for the entire upper limb. It also provides preliminary support for application of modeling results to individuals of varying size. Our ongoing studies will examine muscle scaling in a larger group of subjects.

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