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Imaging two-dimensional displacements and strains in skeletal muscle during joint motion by cine DENSE MR

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Abstract

The objective of this study was to apply cine magnetic resonance imaging (MRI) using displacement encoding with stimulated echoes (DENSE) to measure the dynamic two-dimensional (2D) displacement and Lagrangian strain fields in the biceps brachii muscle. Six healthy volunteers underwent cine DENSE MRI during repeated elbow flexion against the load of gravity. Displacement encoded dynamic images of the upper arm were acquired with spatial and temporal resolutions of $1.9 \times 1.9\,\text{mm}^2$ and 30 ms, respectively. Pixel-wise Lagrangian displacement and strain fields were calculated from the measured images. We extracted the first and second principal strains ($E1$ and $E2$) along the centerline and anterior regions of the muscle. $E1$ and $E2$ were relatively uniform along the anterior region. However, $E1$ and $E2$ were both non-uniform along the centerline region–normalized values for $E1$ and $E2$ varied over the ranges of 0.27–1.35, and 0.45–2.36, respectively. The directions of the first and second principal strains varied throughout the muscle and showed that the direction of principal shortening is not necessarily aligned with fascicle direction. This study demonstrates the utility of cine DENSE MRI for analyzing skeletal muscle mechanics and provides data describing the *in vivo* mechanics of muscle tissue to a level of detail that has not been previously possible.

Keywords: Muscle mechanics; Biceps; Displacement; Strain; DENSE; MRI

1. Introduction

Mathematical models of skeletal muscle are widely used to investigate the causes of movement abnormalities and to analyze surgical treatments. Most models represent muscle properties using simple geometric idealizations that assume that all muscle fibers shorten uniformly (Delp et al., 1990; Zajac, 1989). These simplified models are limited in their ability to accurately represent the *in vivo* behavior of muscles that have complex arrangements of muscle fibers. Recently, several investigators have developed finite-element models of skeletal muscle that allow for representation of realistic three-dimensional (3D) geometries, incorporate the nonlinear active and passive constitutive properties of muscle tissue, and are able to characterize non-uniform shortening within muscles (Blemker and Delp, 2005; Fernandez et al., 2005; Yucesoy et al., 2002). These models have provided new insights into skeletal muscle mechanics; for example, analysis of a finite-element model of the biceps brachii muscle identified how complex features of muscle architecture could contribute to non-uniform strains along muscle fascicles (Blemker et al., 2005).

In order to broaden the utility of finite-element muscle models, methods to rigorously validate predictions made

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by the models are needed. Dynamic magnetic resonance (MR) imaging techniques have made it possible to characterize *in vivo* motion and shortening of skeletal muscle tissue during joint movement. For example, cine phase-contrast (cine-PC) MR images taken of the long head of the biceps brachii showed non-uniform shortening along some muscle fascicles during low-load elbow flexion (Pappas et al., 2002). In that study, the displacements of square regions of interest were calculated by integrating the velocity measurements, and one-dimensional strains were determined by calculating the change in length between square regions that were placed along the muscle fascicles. These data provide valuable *in vivo* measurements to confirm the models' predictions of non-uniform strains along fascicles. However, in addition to non-uniform shortening along muscle fascicles, finite-element models also predict non-uniform strains transverse to the fascicle direction (Blemker et al., 2005)—results that may have important implications on muscle function, but must be verified with imaging techniques that enable measurements of two-dimensional (2D) strain fields.

MR imaging using displacement encoding with stimulated echoes (DENSE) offers a robust method for quantifying 2D strain fields (Aletras et al., 1999a, b; Aletras and Wen, 2001; Kim et al., 2004). Relative to an initial displacement-encoding time, DENSE directly encodes tissue displacement into the phase of the stimulated echo. A sequence of phase-reconstructed images are obtained using cine DENSE MR imaging to achieve pixel-wise spatial resolution and direct extraction of tissue displacements. Based on the pixel-wise displacement measurement, 2D Lagrangian strain fields can be calculated (Spottiswoode et al., 2007). Using a motion phantom, cine DENSE has previously been shown to be highly accurate (Spottiswoode et al., 2007). Cine DENSE has also been validated *in vivo* for myocardial function evaluation (Kim et al., 2004; Gilson et al., 2004).

The goal of this study was to apply cine DENSE MR imaging to measure pixel-wise displacement and Lagrangian strain fields of skeletal muscle. With cine DENSE MR imaging, 2D and 3D pixel-wise displacements were measured within the upper arm during active elbow flexion against the load of gravity. To test the technique with existing published results, we extracted one-dimensional strains along the centerline and anterior regions of the muscle and compared these results to cine-PC imaging results, described by Pappas et al. (2002). We then analyzed the 2D strain fields—we determined the values and directions of the first and second principal strains ($E1$ and $E2$) along the centerline and anterior regions of the biceps brachii muscle. This study demonstrates the utility of cine DENSE MR imaging for analyzing skeletal muscle mechanics and provides data describing the *in vivo* mechanics of muscle tissue to a level of detail that has not been previously possible.

2. Methods

2.1. Volunteer imaging

Six healthy subjects (four male and two female, age 24.4 ± 1.14 yr, height 1.81 ± 0.13 m, weight 74.93 ± 12.67 kg) volunteered for participation in this study. Each subject was scanned using a 1.5T Avanto scanner (Siemens Medical solutions, Erlangen, Germany) after informed consent was obtained. All studies were performed in accordance with the general investigational MR imaging/spectroscopy protocol (IRB-HSR #9039) approved by our institutional review board.

The subjects were positioned supine in the MRI bore, allowing them to perform a full range of elbow flexion–extension (Fig. 1). Each subject's dominant arm was aligned with the longitudinal axis of the scanner, and imaged using a general-purpose flexible radio-frequency receive coil. The subject used the hand of the dominant arm to hold the handle of a

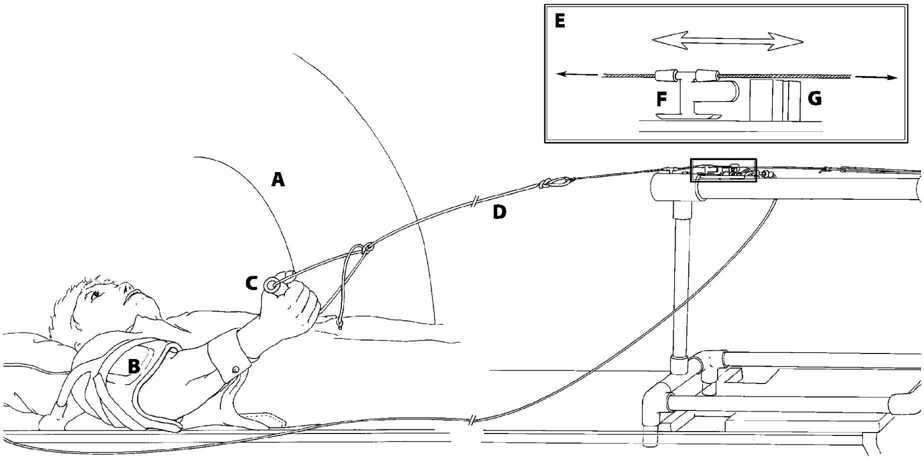

Fig. 1. Experimental setup. The subject was positioned supine in the MRI scanner (A), and a general-purpose flexible radio-frequency receive coil (B) was wrapped around the upper arm. The subject flexed and extended his/her elbow while grasping a handle (C) that was connected via a rope (D) to the triggering mechanism (E). The triggering mechanism consisted of a light emitting diode (LED) and a photodiode that were mounted to blocks (G) on either side of a slider (F). As the subject flexed his/her elbow, the slider moved past the blocks, which allowed the photodiode to detect the LED signal and send a square pulse to the MRI scanner to indicate the beginning of a motion cycle.