Application of Cine DENSE MRI to Studying Skeletal Muscle Mechanics during Joint Motion

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Introduction. Dynamic imaging techniques have enabled *in vivo* characterization of muscle tissue deformations, providing unique data that advance our understanding of muscle mechanics and function. For example, cine phase-contrast (cine-PC) images acquired in the biceps brachii muscle during low-load elbow flexion showed that some regions of the muscle shorten nonuniformly [1], challenging the commonly made assumption that all muscle fascicles shorten uniformly. However, since the displacements determined by integrating cine-PC data are in general averaged over several pixels and the strains calculated are one-dimensional, it is difficult to extract finer resolution displacement and strain fields that are needed to further explore the internal mechanics of the biceps and other muscles. Cine DENSE is a quantitative motion imaging technique that directly encodes tissue displacement into the phase of the stimulated echo [2], allowing for extraction of detailed deformation information, including pixel-wise displacement and Lagrangian strain fields. Cine DENSE has been previously used for myocardial motion tracking [3]. The purpose of the present study was to test the feasibility of using cine DENSE to quantify skeletal muscle displacement and strain.

Methods. An echo-planar cine DENSE sequence was used to acquire displacement encoded dynamic images of the biceps brachii (an elbow flexor) and triceps brachii (an elbow extensor) muscles of five normal volunteers. Each subject was scanned using a 1.5T Avanto scanner (Siemens Medical solutions) after informed consent was obtained. All studies were performed in accordance with protocols approved by our institutional review board. Each subject's dominant arm was aligned with the longitudinal axis of the scanner, and imaged using a flexible general-purpose radio-frequency surface coil. The subjects performed elbow flexion against the load of gravity from nearly full elbow extension to 45º-90º of elbow flexion at a rate of 30 cycles/min. Elbow motion was gated with the onset of the flexion by a photodiode circuit. Eighteen motion cycles were used for each encoding direction. Both long-axis and short-axis view images were obtained. For each view, muscle displacement was encoded in both in-plane directions and in the through-plane direction so that 3D displacements could be measured. For this study, the field of view was 32 x 20 cm and the image matrix was 128 x 80. Other parameters included slice thickness = 8mm, flip angle = 15°, TR = 10 ms, TE = 4.8 ms, ETL = 3, segments = 9, phases = 70, and displacement encoding frequency = 0.05 cycles/mm. Slice following was used to obtain true through-plane motion for the short-axis view.

Results. Example long-axis data at maximum flexion are shown in Fig. 1. The displacement map (B) demonstrates that the antagonistic muscles, i.e. biceps brachii and triceps brachii, are moving in opposite directions during the elbow flexion. The first principal strain (E1) and the second principal strain (E2) are roughly oriented along the fiber direction (C, E) and perpendicular to the fiber direction (D, F), respectively. Fig. 1 also shows that peak superior displacement occurs in the centerline of the muscle. Example mean strains of the anterior boundary and the centerline of the biceps brachii for one volunteer are shown in Fig. 2. E1 and E2 along the anterior boundary were relatively uniform with average values of -0.17 and 0.02, respectively. However, E1 and E2 along the centerline varied as a function of distance from the distal tendon with ranges of -0.05 to -0.4, and 0.15 to 0.69, respectively.

Conclusions. The results from this study demonstrate that cine DENSE is a feasible technique for acquiring *in vivo* skeletal muscle tissue displacements and strains during joint motion. For all subjects, the direction of muscle tissue motion during elbow flexion was consistent with the muscles' mechanical actions, and the peak displacements occurred along the centerline of the muscles. The first principal strains showed nonuniform shortening along the centerline region and uniform shortening along the anterior region, which is consistent with previous cine-PC results [1]. Moreover, these new data suggest that the strains in the direction roughly perpendicular to the fiber direction are also nonuniform throughout the muscle. Cine DENSE provides a reliable means to measure muscle displacement and strain that allow us to understand the complex internal mechanics of skeletal muscle to a level of detail that has not been previously possible.

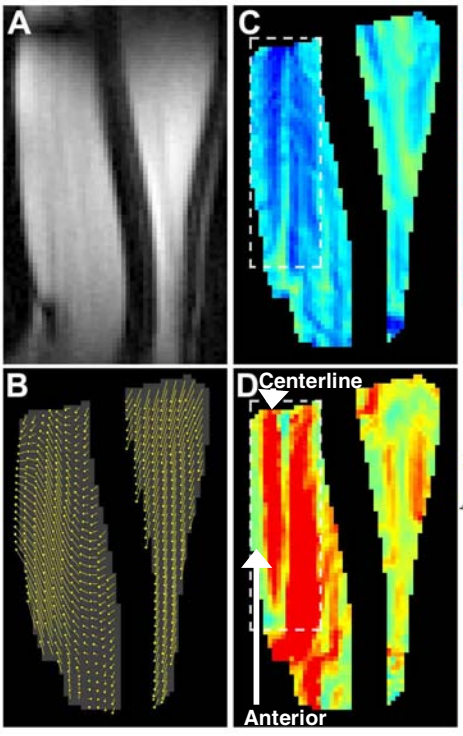

Fig. 1 Example magnitude image (A), displacement map (B), and first (C) and second (D) principal strain maps with corresponding insets (E, F) showing the direction of strain vectors. The displacement map is spatially under-sampled for visualization purposes.

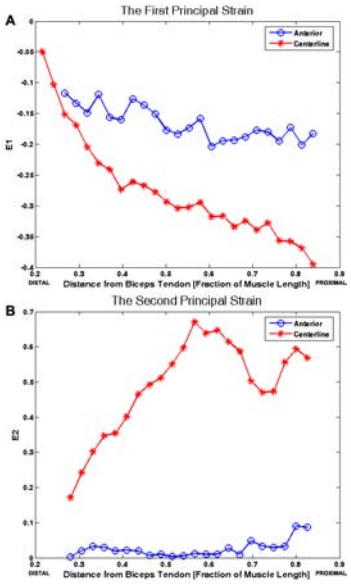

Fig. 2 Example mean first principal strains (A) and second principal strains (B) along the anterior boundary and the centerline of the biceps brachii during elbow flexion. Strains are plotted as a function of distance from the distal tendon, normalized by the length of the biceps brachii long head muscle belly, and positive strains correspond to shortening and negative strains correspond to stretching.

1. Pappas et al. Journal of Applied Physisology 2002; 92:2381-2389.
2. Aletras et al. Journal of Magnetic Resonance 1999; 137:247-252.
3. Kim et al. Radiology 2004; 230:862-871.