Hamstrings and quadriceps muscle displacements during knee joint flexion as determined by 3D DENSE

N. Fiorentino[1], X. Zhong[2], M. Rehorn[2], F. Epstein[2,3], and S. Blemker[1,2]

[1]Mechanical & Aerospace Engineering, University of Virginia, Charlottesville, VA, United States, [2]Biomedical Engineering, University of Virginia, Charlottesville, VA, United States, [3]Radiology, University of Virginia, Charlottesville, VA, United States

Introduction

Skeletal muscles undergo complex three-dimensional deformations as they contract and actuate movement. However, previous studies that capture the motion of muscles *in vivo* with cine MRI techniques have been limited to measurement of muscle tissue in a single plane. For many skeletal muscles, it is impossible to select a single plane that would accurately reflect the overall motion of the muscle. Displacement encoding with stimulated echoes (DENSE) imaging provides direct measurement of tissue displacement (Aletras *et al*., 1999), and this technique has been previously used to reconstruct two-dimensional muscle tissue deformations (Zhong *et al*., 2008). In this study we utilized a three-dimensional (3D) cine DENSE imaging sequence that encodes displacement in three spatial dimensions over a volume of tissue in the thigh during knee joint flexion. As a preliminary assessment of the technique, we analyzed the 3D displacements of the quadriceps and hamstrings muscles, which are the major knee extensor and flexor muscles, respectively.

Methods

A 3D cine DENSE imaging sequence was used to acquire data over a volume of muscle tissue in the mid-to-distal thigh region using a flexible body coil. A stacked-spiral k-space trajectory was utilized for fast data acquisition, and field map acquisition and online spiral deblurring were employed. A balanced four-point method was used for optimal displacement encoding (Zhong *et al*., In press), and three-point phase cycling was used for artifact suppression (Callot *et al*., 2003). The imaging volume was 250 × 250 × 100 mm^3, and the spatial and temporal resolutions were 2.0 × 2.0 × 5.0 mm^3 and 80 ms, respectively. Additional imaging parameters included TR = 15 ms, TE = 1.5 ms, flip angle = 20 degrees, displacement encoding frequency = 0.06, and an imaging time of 25 minutes. Transverse plane magnitude and phase images were reconstructed online and exported for offline segmentation and analysis.

We present data for one normal volunteer, who provided informed consent and was scanned in accordance with protocols approved by our institutional review board. The volunteer was placed head first in the prone position inside a 3T Siemens Trio MRI scanner. Data acquisition was initiated by an external trigger as the volunteer began to move their leg in flexion (i.e. when the leg began to bend after initially being straight). The volunteer continued the flexion motion at a constant rate of 25 flexion cycles per minute with the aid of an auditory metronome sent in over scanner headphones.

Three-dimensional tissue deformations were reconstructed by extending algorithms that had been previously developed for 2D analyses (Spottiswoode *et al*., 2007). Twenty transverse slices were analyzed over twelve time frames, which corresponded to 80% of the flexion motion. The quadriceps and hamstring muscle groups were manually segmented on each transverse slice and time frame (Fig. 1). In each of the time frames after the first, DENSE displacements were used to map the location of pixels in three dimensions back to the initial time frame. Scattered data interpolation using radial basis functions (Hardy, 1971) was then employed to determine the position of the first frame's pixels in each of the later time frames. Tracked tissue locations were fit in time with a 6^{th} order polynomial and used for finding displacements of the quadriceps and hamstrings muscle groups. Tracked tissue locations were plotted for each transverse slice and time frame, where pixels were colored by displacement magnitude from the first frame to highlight regional differences in displacement within the muscle groups. In addition, tissue displacements were averaged over each slice to demonstrate the relative motion of the quadriceps and hamstrings muscle groups.

Results

The quadriceps and hamstrings were clearly identifiable in the magnitude and phase images (Fig. 1a,b). The data show that each muscle moves in a complex non-planar fashion and displacements are spatially dependent within muscle groups (Fig. 1c,d). Moreover, the reconstructed three-dimensional displacements demonstrate that antagonist muscles (e.g., the hamstrings and the quadriceps) are generally moving in opposite directions during knee flexion, as shown in Fig. 2 by the plot of through-plane displacements for the last time frame displayed in Fig. 1. Averaged over all transverse slices, the mean (±SD) through-plane displacement for the hamstrings group was 2.9±1.2 mm, and for the quadriceps muscle groups was -1.4±0.7 mm. The average displacements in the horizontal direction (i.e. left-right direction), with respect to the images in Fig. 1, were -0.5±0.5 mm for the hamstrings and -0.1±0.9 mm for the quadriceps. For the up-down direction, displacements were 1.0±0.4 mm for the hamstrings and -0.2±0.5 mm for the quadriceps.

Conclusion

This study demonstrates that 3D cine DENSE MRI is a feasible method for capturing the 3D deformation of skeletal muscle tissue volumes. Further developments will include shortening scan times, extending the imaged volume, and comparing the displacement and strain of individual muscles. The data captured by 3D cine DENSE MRI can also be used to validate computational models of skeletal muscle and to explore the mechanics of normal, disease, and injured muscle tissue.

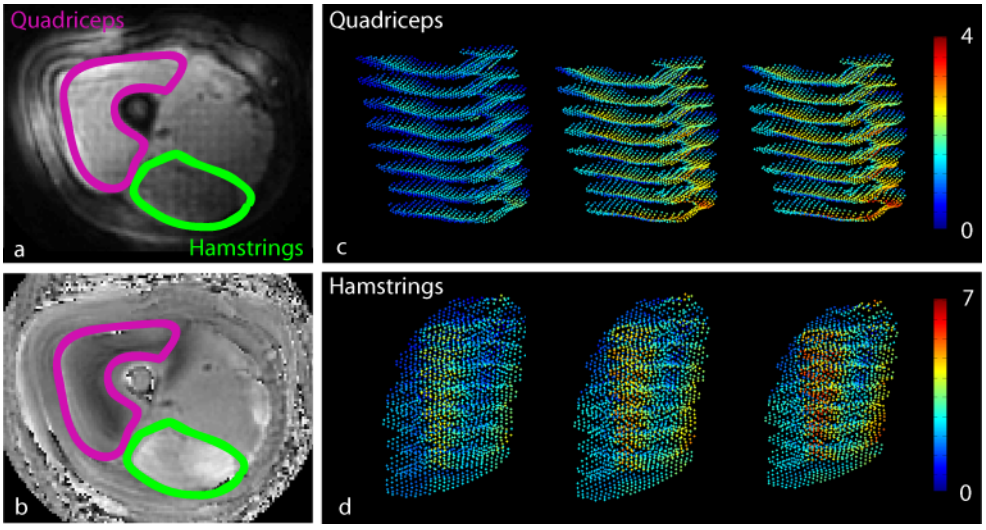

Fig. 1. Example magnitude (a) and phase-reconstructed (b) images in the transverse plane with encoding in the through-plane direction and quadriceps and hamstrings muscle group segmentations. Tracked tissue locations at 3 time frames for the quadriceps (c) and hamstrings (d) muscle groups with displacement magnitude (in mm) indicated by color, as viewed anteriorly and posteriorly, respectively, with the knee at the bottom of the plots.

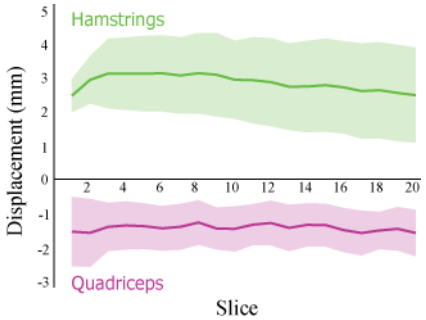

Fig. 2. Through-plane displacement (in mm) averaged across the hamstrings and quadriceps muscle groups for the last time frame in Fig. 1.

References

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