MRI-based 3D Estimation of Muscle Architecture and Strain during Contraction

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Summary

DT-MRI and image registration are used to estimate whole-skeletal muscle architecture and 3D strains during isometric contractions, elucidating relationships between architecture and strain development in skeletal muscle.

Introduction

Skeletal muscle architecture is a major determinant of muscle function. Nevertheless, assessments of muscle architecture and strain during contraction are limited to local coverage using ultrasound [1,2], or low contraction intensities using magnetic resonance imaging (MRI) [3]. Diffusion tensor MRI (DT-MRI) provides 3D representations of muscle architecture during rest, but long scan times preclude its use during contraction. Image registration of structural MRI images, conversely, can map muscle displacement and strain during passive motion and contraction [4,5]. Image registration and DT-MRI can be used to estimate changes in muscle architecture during passive motion [6] and potentially during contraction. The goal of this study was to estimate muscle architecture and strain during isometric contraction using DT-MRI and structural MR image registration. We hypothesized that a) muscle fiber-tract length (L_{FT}) will decrease, while pennation angle (α) and curvature (κ) will increase, during isometric contraction and b) architecture at rest will be correlated to strain during contraction.

Methods

Following IRB approval, the right lower leg of healthy participants (n = 7) was imaged in a 3T MRI system, with the ankle placed at 10˚ plantarflexion in an MR-compatible force-measuring device. Structural fat-water images (scan duration = 36.2 seconds) were obtained during rest and while the participant was holding an isometric dorsiflexion 40% maximum voluntary contraction (MVC). DT-MRI data was obtained during rest. Participant and MRI analysis details can be found in [6]. Tibialis anterior (TA) muscle fiber-tracts during rest were generated from the DT-MRI data. The displacement field mapping the TA muscle deformation from rest to contraction was obtained via 3D Demons registration (accumulated field smoothing = 1.5, 2,000 iterations, 4 pyramids) of structural water images. The displacement field was smoothed and used to transform the DT-MRI fiber-tracts from rest to contracted state and to compute the mean along-fiber strain, along-fiber shear, and cross-fiber shear in each fiber-tract [7]. Mean whole TA muscle L_{FT}, α, and κ of each participant were measured from the fiber-tracts during rest and contraction and compared using paired t-tests. Fiber-tracts from each participant were grouped into bundles of similar architecture and the mean strain invariants and resting architecture estimates of each bundle were computed and correlated using repeated measure correlations.

Results and Discussion

Mean TA muscle fiber-tract length (L_{FT}) significantly decreased, while pennation angle (α) and curvature (κ) significantly increased during isometric dorsiflexion 40% MVC contraction (Table 1), in agreement with ultrasound-based observations [1]. Mean bundle along-fiber strain and along-fiber shear were significantly correlated to resting α and along-fiber shear was significantly correlated to resting L_{FT} (Figure 2), showing how muscle architecture influences strain development during isometric contraction.

Table 1: TA muscle architecture estimates during rest and contraction.

Architecture Estimate	Rest	Contraction	p-value
L_{FT} (mm)	70.1 ± 7.3	64.0 ± 7.0	<0.001
α (˚)	10.3 ± 0.8	11.4 ± 1.3	0.015
κ (m^{-1})	4.4 ± 0.7	6.5 ± 1.2	<0.001

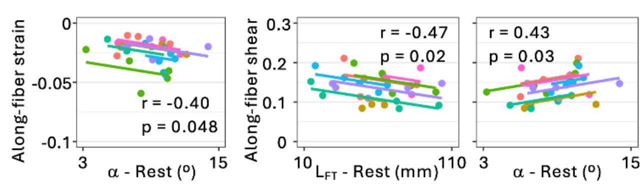

Figure 2: Repeated measure correlations between bundle strain invariants and architecture estimates during rest.

Conclusions

DT-MRI combined with structural image registration can estimate whole muscle architecture and 3D strain during contractions. The correlation between resting architecture and strain development in the TA muscle during 40% MVC isometric contractions highlights their relationship.

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