DTI-Based Fiber Tracking Reveals A Multifaceted Alteration Of Pennation Angle In Tibialis Anterior Muscle Upon Muscle Lengthening

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INTRODUCTION

Diffusion-tensor magnetic resonance imaging (DTI) offers great potential for understanding structure-function relationships in skeletal muscle (Sinha (2006), Lansdown (2007)). The basis for these studies is that the diffusion of water is greater along the long axes of muscle fibers than along their transverse axes. This anisotropy can be characterized using the diffusion tensor, with the orientation of the principal eigenvalue corresponding to the long axis of the muscle fiber. These local, voxel-based directions can be combined by a fiber tracking algorithm to reconstruct the whole-muscle architecture. The fiber tracking data can be used to characterize important muscle architectural parameters, such as pennation angle (θ), fiber length, and physiological cross-sectional area. These parameters influence the mechanical behavior of the muscle and are altered upon active or passive muscle lengthening or shortening. The goal of this study was to determine how θ changes in three dimensions upon muscle lengthening.

METHODS

DTI and anatomical MR images were acquired of the tibialis anterior (TA) of 6 subjects with the foot in 0˚ of plantarflexion (anatomical position), +15˚ of plantar flexion, and at 0˚ on a different day. Data were obtained with a 3T scanner using a double flexible surface coil covering the length of the TA. For anatomical reference a T_1 weighted scan was obtained: FOV=192×192 mm^2, matrix size=256×256, slice thickness =3 mm, 112 slices, TR=0.5 s, TE=18.6 ms. DTI images were acquired in 5 stacks, using an EPI sequence with the same geometric parameters, 128×128 reconstructed matrix, 4 excitations, TR= 5 s, TE=46 ms, b=500 s/mm^2, and diffusion weighting in 6 directions specified according to Jones (1999).

Image registration was performed of 1) the diffusion weighted images to the b=0 image, 2) the DTI stack to the adjacent stack, and 3) DTI set to the anatomical image set. From the anatomical images, the borders of the TA were traced and the position of the central aponeurosis was digitized. A 3D mesh reconstruction of the aponeurosis was defined with 280 rows × 100 column density and the points of intersection were used as seed points for fibertracking. Fibertracking was performed by following the direction of greatest diffusion from the seed points along each of the deep and superficial aspects of the TA's aponeurosis. For each fiber tract, position vectors were formed between the seed point and each of its first five points. For each point, the angle was calculated as the angle between the position vector and the plane tangent to the seed point from which that fiber tract emerges. θ was calculated as the mean of these 5 points. The mean θ was calculated for 50 evenly spaced segments along the aponeurosis (10 rows and 5 columns).

A 3-way repeated measures ANOVA was performed on the difference between the two foot positions with compartment, rows and columns as factors.

RESULTS AND DISCUSSION

Example of fibertracking results are displayed in Figure 1. The mean pennation angle was larger in the deep compartment than in the superficial compartment (Figure 2) ($p=0.044$), as was demonstrated before (Lansdown (2007)). The pennation angle was larger proximally than distally. θ did not differ in any location along the aponeurosis when the 0˚ measurement was repeated.

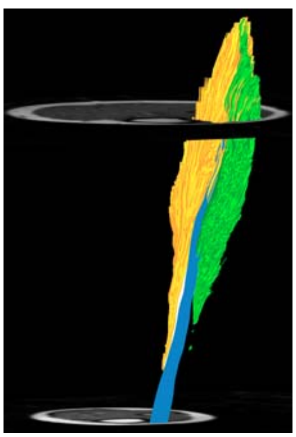

Figure 1: Example of fibertracking results. Fiber tracts from the deep compartments are indicated as gold-shaded lines and from the superficial compartment as green-shaded lines. The aponeurosis is indicated in blue.

The change in θ was larger in the proximal portion of the muscle than in the distal portion ($p=.003$), which is to be expected as the distal part of the aponeurosis is known to be more stiff. There was a tendency for the θ change to be greater in the posterior portion of the muscle ($p=0.069$), which might arise from a larger axial displacement of this part of the aponeurosis. This tendency was greater in the proximal part of the muscle than in the distal part of the muscle (columns × rows interaction, $p=.047$). Also, this interaction occurred to a different extent for both compartments (compartment×rows ×columns $p<0.0005$), with the change in angles being larger and more heterogeneous

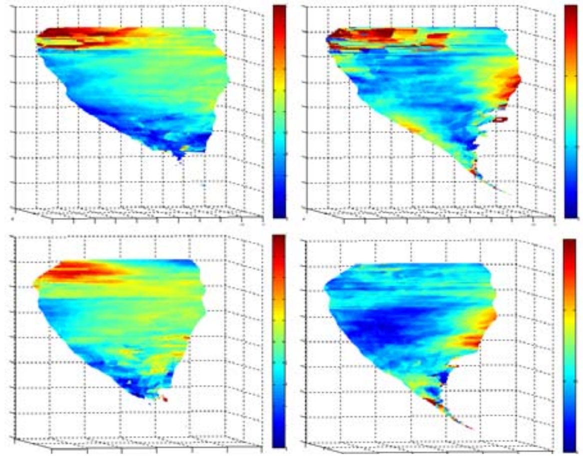

Figure 2: Distribution of pennation angles along the aponeurosis. Left: superficial compartment, right: deep compartment. Upper row: foot at 0˚, bottom row: foot at 15˚. Color bars indicate θ in degrees (left: 0-20˚, right 0-15˚)

in the superficial compartment than in the deep compartment. Therefore, upon muscle lengthening a 3D alteration of the muscle's pennation properties occurs.

CONCLUSIONS

DTI-based fibertracking enables the 3D reconstruction of a multifaceted alteration of pennation angles upon muscle lengthening. These data can be used to improve the understanding of structure-function relationships in muscle.

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