DTI-based fiber tracking reveals a multifaceted alteration of pennation angle and fiber tract length upon muscle lengthening

A. M. Heemskerk¹, and B. M. Damon¹
¹Vanderbilt University Institute of Imaging Science, Nashville, TN, United States

Introduction
Skeletal muscles exhibit a close relationship between muscle structure and function. Understanding this connection is important for understanding muscle force production and movement. Ultrasound (US) is a common used modality to determine important muscle architectural parameters, such as pennation angle (θ) and fiber length (L_f). However, US is typically used to determine these parameters at the muscle mid belly region and most of its applications in skeletal muscle to date have used 2D techniques. This is important as θ and L_f can vary along the muscle and muscle architecture may change heterogeneously upon changes in muscle length. Recently, it has been shown that DTI-based fiber tracking in skeletal muscle offers exciting possibilities to reconstruct the 3D muscle architecture (1-3). Therefore, the goal of this study was to determine how θ and fiber tract length (L_t) changes along the aponeurosis upon passive muscle lengthening.

Methods
Subjects: Anatomical and DTI datasets were obtained from 6 healthy subjects (3 male). The tibialis anterior (TA) muscle was measured with the foot positioned in -15˚, +5˚ and +30˚ of plantar flexion; the order was randomly assigned.
MRT: Data were obtained with a Philips 3T scanner using 2 double flexible surface coils covering the length of the TA. For anatomical reference both a PD scan and a T2w scan were obtained: FOV=192×192 mm², acquired matrix=256×128 (reconstructed at 512×512), slices thickness=6 mm, 55 slices, PD: TR/TE=4152/11 ms or T2w: TR/TE=7557/30 ms. DTI data were acquired in 5 continuous stacks with a total of 55 slices, using an EPI sequence with FOV=192×192 mm², acquired matrix=96×64 (reconstructed at 128×128), TR/TE=3300/48 ms, b=500 s/mm², and 10 diffusion gradient directions. Image processing: Image registration was performed of Dw to b=0, DTI stack to the adjacent stack, and DTI set to T2w. From the PD images, the borders of the TA were traced and the positions of both the superficial and deep aspects of the central aponeurosis were digitized and reconstructed in a 3D mesh with 200×100 density. The points of intersection were used as seed points for fiber tracking, which occurred in the direction of ε1 and terminated at the muscle border, if FA<0.15, or if successive points had a curvature of >45˚. After fiber tracking, a quantitative assessment of the fiber tracts was performed to exclude erroneous fiber tracking results (4).

Data analysis: For each fiber tract, the θ was calculated as the mean of the angle between the plane tangent to the seed point and the position vectors of the first 5 points along the tract. L_t was calculated as the sum of the distance between consecutive fitted points along the tract. Median θ and L_t values were calculated for 18 evenly spaced segments along the aponeurosis (6 rows and 3 columns). A 3-way ANOVA was performed with foot position, rows and columns as factors. Only the proximal 4 columns were included in the analysis as the most distal columns had low reproducibility (5).

Results and Discussion
As expected, upon muscle lengthening θ decreased (p<0.005) and L_t increased (p<0.001) (Figures). θ decreased from 18˚ to 14˚ while L_t increased from 33 mm to 52 mm in the midbelly region. This is comparable with previous US findings, although they report a longer L_t (6). Along the aponeurosis, the changes were heterogeneous for θ (p<0.031), with the largest changes in the proximal-anterior portion of the aponeurosis (Fig 1). A possible explanation for this is that the aponeurosis is less stiff in the proximal part, although no length changes in aponeurosis were detected. There was no detectable overall heterogeneity in L_t changes.

Conclusion
This study shows that DTI-based fiber tracking is able to determine the 3D changes in θ and L_t upon muscle lengthening. In addition, the changes in θ are heterogeneous along the aponeurosis. This offers exiting new possibilities to study and model the structure-function relationship in muscle.

References
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