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

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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_{ft}) 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.

MRI: 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 T_2w scan were obtained: FOV=192×192 mm^2, 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 mm^2, acquired matrix=96×64 (reconstructed at 128×128), TR/TE=3300/48 ms, b=500 s/mm^2, 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 T_2w. 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 ε_1 and terminated at the muscle border, if FA<0.15, or if successive points had a curvature of >45˚. After the 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_{ft} was calculated as the sum of the distance between consecutive fitted points along the tract. Median θ and L_{ft} 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).

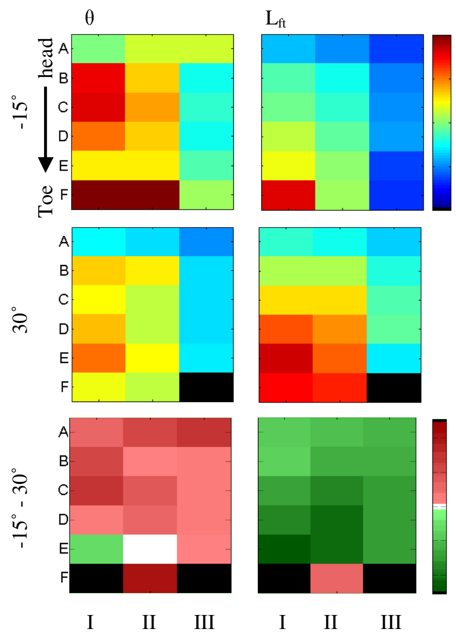

Fig 1) Average θ and L_{ft} for the two extreme foot positions. I, II, and III indicate the anterior, middle, and posterior portion of the aponeurosis, respectively. A through F indicate the head and toe direction. Color bar: θ: 0-30˚ and L_{ft}: 0-80 mm. Bottom row depicts -15˚ minus 30˚, color bar: -12.8-12.8.

Results and Discussion

As expected, upon muscle lengthening θ decreased ($p<0.005$) and L_{ft} increased ($p<0.001$) (Figures). θ decreased from 18˚ to 14˚ while L_{ft} increased from 33 mm to 52 mm in the midbelly region. This is comparable with previous US findings, although they report a longer L_f (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_{ft} changes.

Conclusion

This study shows that DTI-based fiber tracking is able to determine the 3D changes in θ and L_{ft} 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.

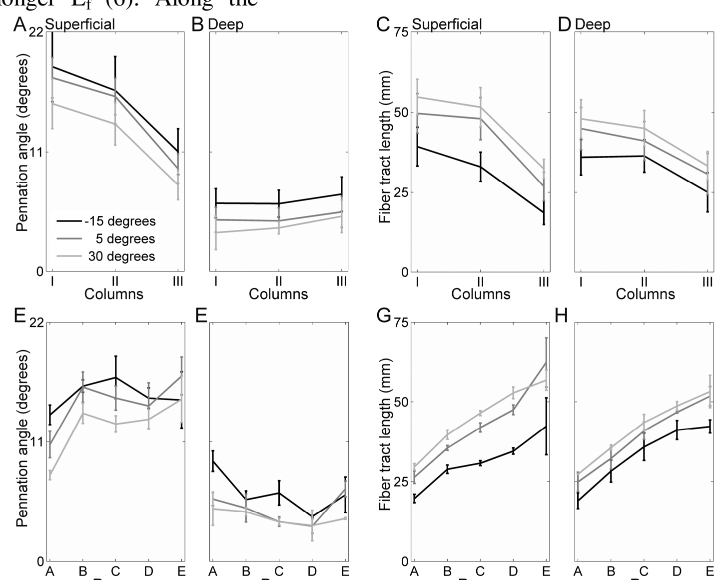

Fig 2) Mean values for each column (A-D) or each row (E-H).

References

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