Objective 3D-ultrasound analysis of tibialis anterior muscle architecture and aponeurosis geometry

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Summary

Quantification of a muscle's entire in-vivo architecture is challenging. We present an automated 3D ultrasound (3DUS) method to objectively quantify the architecture and central aponeurosis geometry of the entire human tibialis anterior (TA) muscle at rest and during contraction. Initial results from ongoing data collection reveal between- and within-subject variability in aponeurosis geometry, whereas passive fascicle and fibre length changes between joint angles from 3DUS and diffusion tensor imaging (DTI) were similar. Our method leverages 3DUS to objectively assess a muscle's entire architecture.

Introduction

Skeletal muscles power movement and absorb energy, and their architecture affects both force and power capacity. Thus, assessing muscle architecture and its changes is essential for understanding muscle and its adaptations to training or disuse. However, evaluating in-vivo muscle architecture is challenging due to each muscle's heterogenous 3D structure. Current imaging methods, like DTI, are costly, time-consuming and require numerous assumptions to reconstruct 3D architecture at rest, whereas standard B-mode ultrasound allows dynamic assessment, but only in a subjectively chosen 2D plane. Thus, we developed an automated 3DUS method to objectively quantify TA muscle architecture and central aponeurosis geometry at rest and during contraction.

Methods

As data collection is ongoing, so far four participants (age: 37±8 yr [mean ± SD], one woman) underwent 3DUS and DTI scans, and nine participants (26±2 yr, four women) underwent 3DUS scans at rest and during fixed-end contractions. 3DUS and DTI scans of the TA muscle from both legs were performed on the same day, at ankle joint angles of -5°, 15° and 35° plantar flexion (0° represents a 90° angle between footplate and tibia). For 3DUS scans, an ultrasound transducer (ArtUs, 60 x 50 mm, width x depth) coupled with a gel pad (ParkerLab) was swept with a relatively constant velocity and pressure over the participants' shanks to image the entire TA muscle belly. The ultrasound transducer was attached to a 3D-printed case with four reflective markers and tracked by four cameras (Flex3) to determine the relative location and orientation of each ultrasound image in 3D space. Spatial and temporal calibration, as well as data collection, were performed in Stradwin, and ultrasound images were recorded at ~67 Hz. Data processing involved: 1) reslicing the data into a grid with an isotropic voxel size of 0.25 mm; 2) segmenting TA's muscle and central aponeurosis borders semi-automatically; 3) reconstructing these structures in 3D using a crust algorithm, and; 4) creating a rotation matrix for the central aponeurosis mesh based on a weighted principal component analysis. This matrix was then applied to the muscle and aponeurosis meshes and the image volume to objectively define a coordinate system, with the third principal component defining muscle thickness. Aponeurosis geometry was then quantified (Fig. 1) and a modified muscle fascicle tractography algorithm [1] was applied to each parasagittal slice in the XZ plane to detect muscle fascicles. Fascicles were then reconstructed in the XZ plane by linearly extrapolating their extremities between the muscle and aponeurosis meshes. To compare fascicle with fibre length changes based on diffusion MRI data, DTI scans (Siemens MAGNETOM Prisma 3T scanner, Siemens Healthineers, Erlangen, Germany) of both legs were performed with a 15 cm field of view from 6 cm below the fibular head. 42 diffusion gradients with 6 b-values were acquired and data were analysed and tractography performed according to [2] using QMRITools. Watermaps derived from a Dixon-based sequence served as references and were used for automated segmentation of the TA.

Results and Discussion

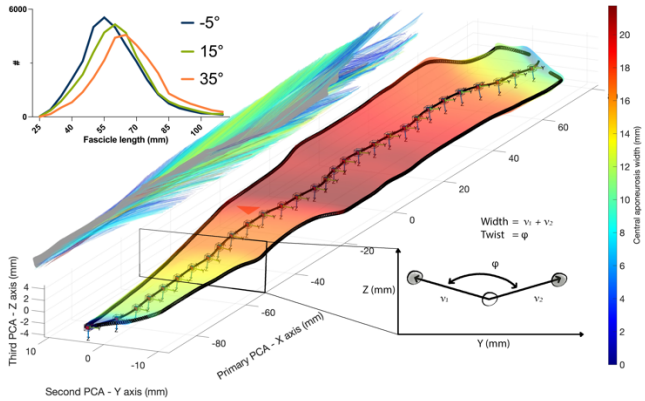

Figure 1: Example (n=1) of TA central aponeurosis analysis, tracked fascicles in 3D, and fascicle length distributions (top left).

Preliminary results reveal between-subject and within-subject (between-leg) variability in aponeurosis geometry, but similar fascicle/fibre length changes between subjects and legs.

Conclusions

By objectively defining imaging planes based on 3DUS data, we created a repeatable muscle architectural analysis tool to improve our understanding of muscle adaptation.

References

[1] Kilpatric et al. (2023). *J Appl. Biomech.*, 39(6):421-431
[2] Forsting et al. (2022). *NMR in Biomed.*, 35(7):e4707