In Vivo Muscle Fiber Curvature Measurements Using DT-MRI

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Introduction

We have previously shown that diffusion-tensor (DT) MRI-based muscle fiber tracking can reproducibly quantify aspects of human muscle architecture in 3D, including fiber tract length and pennation angle (1,2). Another important architectural parameter is muscle fiber curvature, which influences the development of intramuscular pressure during contraction; this pressure, in turn may influence the patterns of perfusion during contraction (3,4). However, we know of no previous use of DT-MRI to measure human muscle fiber curvature. It is likely that the curvature estimates are elevated because of noise in the DT-MRI data, as this would add additional variability to the spatial positions that define the muscle fiber tracts. Thus the purposes of this study were 1) to investigate the potential for polynomial fitting of the fiber tracts to mitigate the effects of noise on curvature measurements, as revealed by reduced apparent curvature values and 2) to investigate the changes in fiber curvature consequent to changes in muscle-tendon unit (MTU) length.

Methods

Subjects Anatomical and DT-MRI datasets were obtained from 5 healthy subjects. The tibialis anterior (TA) muscle was measured with the foot positioned in -15° and +30° of plantar flexion (producing short and long MTU lengths, respectively); the order of measurements was randomly assigned.

MRI Anatomical and DT-MRI data were obtained with a Philips 3T MR imager/spectrometer using 2 pairs of flexible surface coils covering the length of the TA. For anatomical reference, a proton density-weighted scan and a T_2-weighted scan were obtained with FOV=192×192 mm^2, reconstructed matrix=512×512, slice thickness=6 mm, and 55 slices. DTI data were acquired in 5 continuous stacks of 11 slices each, 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 Analysis Image registration was performed of the diffusion-weighted images to the non-diffusion weighted images, of the DTI stack to the adjacent stack, and of the DTI set to the T_2-weighted image. Fiber tracking was performed as previously described (1,2,5). After fiber tracking, the *x*, *y*, and *z* positions along each of the originally reconstructed fiber tracts (the *Original* tracts) were fitted as functions of point number to 2nd order polynomial functions. Two smoothed fiber tract data sets were formed by solving the polynomials at intervals of 1 pixel (equal to the spatial resolution of the original tracts) and 0.5 pixels (*Smoothed_1.0* and *Smoothed_0.5*, respectively). A quantitative assessment of the fiber tracts was performed for each of the datasets to exclude erroneous fiber tracking results, essentially the same as previously described (5), but updated to include curvature.

Fiber Tract Analysis For each point along the fiber tract, the curvature (κ) was determined using the Frenet-Serret formulae. To do so, the tangent line (T) between each successive pairs of points was determined and the rate of change in the tangent line with respect to spatial position, $d\mathrm{T}/ds$, was computed. The normal unit vector to $d\mathbf{T}/ds$, $\hat{\mathbf{n}}$, was measured and the curvature was calculated by rearrangement of $d\mathrm{T}/ds = \kappa\hat{\mathbf{n}}$ to solve for κ.

Statistical Analysis The mean value of κ was determined for the fiber tracts originating from the superior, middle, and inferior thirds of the TA's central aponeurosis. To determine the effect of fiber smoothing on the curvature estimates *in vivo*, a one-way ANOVA, followed by Tukey's honestly significant difference (HSD) test, was performed for the mean values of κ for the superior third of the muscle, using the data from the *Original, Smoothed_1.0,* and *Smoothed_0.5* datasets. The results will demonstrate a significant effect of fiber smoothing on the κ estimates. Therefore, the data from the *Smoothed_0.5* dataset were used to test the effect of fiber rotation on fiber curvature, using a 2-factor ANOVA (Rotation×Superior-Inferior Position). The ANOVA was followed by Tukey's HSD test. Analyses were conducted separately for the superficial and deep compartments of the muscle.

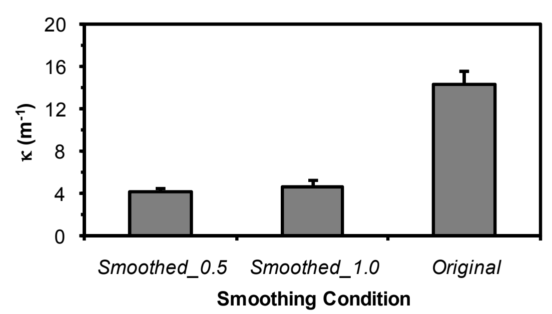

Figure 1. Mean and SE of κ for the original and smoothed tracts originating from the superior portion of the aponeurosis in the superficial compartment of the TA. *p<0.05 *vs.* the smoothing conditions.

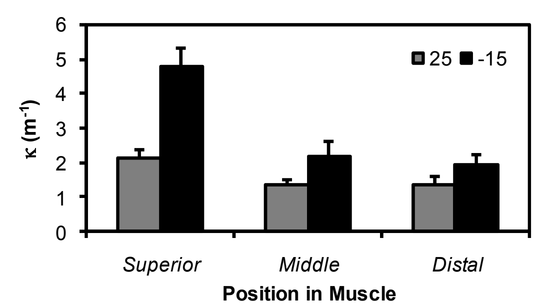

Figure 2. Mean and SE of κ for the *Smoothed_0.5* fiber tracts in the superior, middle, and inferior portions of the muscle (deep compartment). κ was greater in the superficial portion of the muscle than in other regions and increased with foot rotation to the dorsiflexed position.

Results and Discussion

Figure 1 shows the mean and standard error (SE) for the κ estimates from the *Original, Smoothed_1.0,* and *Smoothed_0.5* datasets for fiber tracts in the superficial compartment with the foot in the +25° position. The curvature estimates were significantly greater for the unsmoothed tracts (p<0.01), but did not differ between the *Smoothed_1.0* and *Smoothed_0.5* datasets. Similar trends (not shown) were observed with the foot in the -15° position. Figure 2 shows the mean and standard error for the κ estimates for the superior, middle, and inferior portions of the muscle in the -15° and +25° of plantar flexion conditions, for the deep compartment of the muscle. In each compartment, the mean value of κ was greater in the superior portion of the muscle than in the distal portion of the muscle (p<0.01). Also, as the foot was dorsiflexed, the mean value of κ increased (p<0.05 for the superficial compartment; p<0.01 for deep compartment).

Conclusions

Second order polynomial smoothing of the fiber tracts reduced the apparent curvature values. The reduction is not an effect of a difference in spatial resolution, as the reduction occurred for both the *Smoothed_1.0* and *Smoothed_0.5* datasets. Rather, the reduction is likely due to a mitigation of the effect of noise. When the foot is rotated from a plantarflexed position to a dorsiflexed position, the curvature of the muscle fibers increases.

References

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