Changes to 3D muscle fascicle geometry during contraction

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INTRODUCTION

Muscle is a three dimensional (3D) entity with varying shape across the length of the muscle and changes shape during contraction. Changes in muscle shape can influence the orientation of the fascicles within the muscle [1]. Dissection studies examining 3D muscle fascicles architecture have reported regional variations in the fascicle architecture [2]. 2D ultrasound studies have shown that the muscle fascicles are curved, and the curvature depends on the contraction state of the muscle [3]. Muscle modeling studies have predicted 3D curving of the fascicles [4], and dissection studies in human first dorsal interosseous muscle (FDI) [5] and animal muscles [6] have shown 3D helical curvature of fascicles.

Previous work on muscle architecture has been mostly in 2D, and a few diffusion tensor MRI and 3D ultrasound studies have quantified the 3D fascicles orientations in passive muscles. 3D fascicle architecture has not been studied during active muscle contractions.

The aim of this study was to obtain the map of muscle fascicle orientations and curvatures in human triceps surae during different muscle lengths and contraction states.

METHODS

Ultrasound images were obtained from six male subjects using a linear ultrasound probe (Echoblaster, Telemed, LT) recording at 20 Hz. Lateral gastrocnemius (LG), medial gastrocnemius (MG) and soleus were imaged for isometric ankle plantarflexions at a fixed knee angle of 135°, a range of ankle angles (-15°, 0, 15 and 30°) and ankle torques (0, 30 and 60 % maximum voluntary contraction (MVC). Images were analyzed to obtain the 2D orientations grids in the image planes. 2D orientation grids from each ultrasound image were reconstructed into 3D grids using 3D position and orientation of the scanning probe using an optical position sensor (Optotrak Certus®, NDI, Ontario). The muscle volume was divided into 5×5×5 mm^3 voxels, which contained a representative value for fascicle orientation represented in polar coordinates as polar angle (considered as pennation angle, β_f) and azimuthal angle (φ_f) [7].

3D curvature maps were obtained from the orientation grids. Fascicle trajectories were tracked locally around each voxel. The local trajectories were used to obtain the curvature magnitude (κ_c) and orientation of normal to curves in polar co-ordinates (β_c and φ_c) using the Frenet-Serret formula.

General linear model ANOVA was used to test the effects of muscle region, ankle angle and ankle torque level on the fascicle orientation, fascicle curvature and orientation of the normal to the curve. Post-hoc Tukey tests were performed to determine the regionalization effects, torque and ankle angles on the dependent variables. The results obtained were considered significant for p-value <0.05.

RESULTS AND DISCUSSION

3D fascicle orientations were regionalized (Figure 1) in all the three muscles (LG, MG and the soleus), and the variations were the maximum along the length of each muscle. In LG, β_f increased from 11.2° to 14.5°, and, φ_f increased from 92.4° to 103.4° from proximal to distal end of the muscle. The regional variations of φ_f indicated helical arrangement of fascicles that was further supported by the regionalization of the fascicle curvature magnitude and direction. Fascicle orientation and curvature changed significantly with contraction level and ankle angle (table 1). There was also a significant interaction between ankle torques and angles on the fascicle architecture. In LG, β_f decreased as the ankle angle increased for 0% MVC but for higher torque levels this trend gradually vanished.

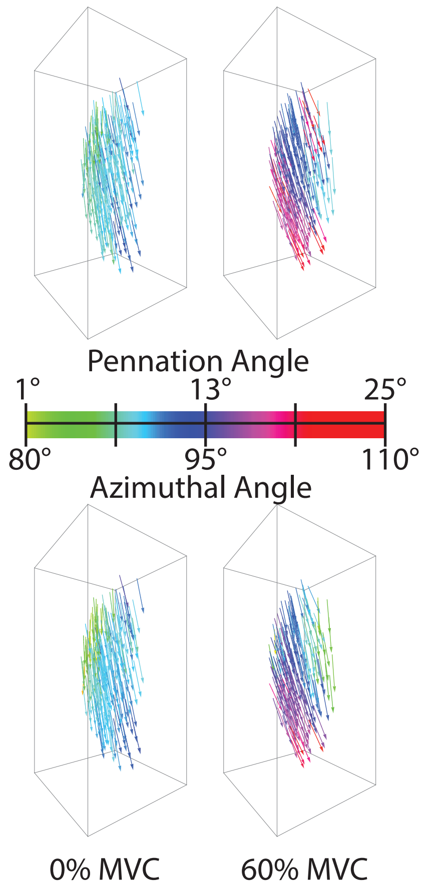

Figure 1: 3D fascicle orientations in the LG for one representative subject at 30° ankle angle. The images show the regionalization of pennation angle and azimuthal angle in the muscle and the change in orientations with torque level.

A curved fascicle generates a pressure difference across the curve with the pressure being greater on the concave side and the magnitude of the pressure differential increasing with the increase in the curvature [4] The curvature maps obtained in this study may be used to predict the intramuscular pressure distributions for different contraction states of muscles.

CONCLUSIONS

This is the first time that 3D fascicle architecture has been quantified in muscles during different contraction states and related to the ankle joint angle and joint torque. The 3D fascicle orientation is regionalized across each muscle in the triceps surae and depends on the muscle length and contraction level. Azimuthal angle (φ_f), a new parameter obtained as a virtue of 3D quantification methods, changed by the same magnitude as the typical 2D orientation measure of pennation angle. The fascicles curve in 3D and curvature magnitude and direction depended on contraction state of the muscle. The 3D curving of the fascicle shows that the 2D planar imaging is not sufficient to capture the complexity of fascicle architectural.

REFERENCES

1. Wakeling JM, et al. *Philos Trans R Soc Lond B Biol Sci* **366**, 1554-1564, 2011
2. Agur AM, et al. *Clin Anat* **16,** 285-293, 2003
3. Muramatsu T, et al. *J Appl Physiol* **92,** 129-134, 2002
4. van Leeuwen JL and Spoor CW**.** *Philos Trans R Soc Lond B Biol Sci* **336**, 275-292, 1992.
5. Infantolino BW, et al. *Anat Rec (Hoboken)* **295**, 1174-1180, 2012
6. Alexander RM. *J Mar Bio Assoc* **49**, 263-290, 1969
7. Rana M, et al. *J Biomech 44*, 2129-2135, 2011

Table 1: Mean (± standard error of mean) fascicle orientations and curvature values for different ankle angles and torque levels in LG.

Ankle Angel	% MVC	β_f (°)	φ_f (°)	κ_c (m^{-1})	β_c (°)	φ_c (°)
-15°	**0%**	13.9 ± 0.05	93.9 ± 0.04	3.7 ± 0.05	92.8 ± 0.16	200.6 ± 1.52
-15°	**60%**	12.7 ± 0.05	98.2 ± 0.05	4.1 ± 0.05	91.1 ± 0.16	182.8 ± 1.45
30°	**0%**	10.5 ± 0.03	93.9 ± 0.04	3.4 ± 0.05	90.8 ± 0.14	190.2 ± 1.5
30°	**60%**	12.9 ± 0.05	97.6 ± 0.06	4.1 ± 0.06	91.7 ± 0.15	195.2 ± 1.3