Changes in Pinnation Angle and Fiber Length of Muscles under Plantar- and Dorsi-flexion and Force Production - In-vivo, DTI based Fiber Tractography in Humans.

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Introduction: Diseases of muscle such as muscle dystrophy, prolonged bed-rest or near-zero gravity space flight almost always result in reduced force production. This is a consequence of changes in several muscle physiological parameters such atrophy, reduced neurological activation, and changes in architectural parameters such as pennation angles, fiber length, and consequently, muscle physiological cross-sectional area. The objective of this study was to systematically study, using in-vivo diffusion-tensor based fiber-tractography, the pinnation angles, fiber-lengths and overall arrangement of fibers in muscles of the lower leg, and changes these parameters undergo upon plantar flexion movement and active force production.

Materials and Methods: One subject was used to optimize the MR DTI imaging protocol on a 3T GE Excite system, with a dedicated 8-channel leg coil (Millenium, USA), and computer-controlled hydraulic foot-pedal system. The optimized protocol was then used on 4 different subjects, all male and not atheletes (under IRB approval). For optimization, the following comparisons were made: Diffusion weighted Spin Echo EPI, Dual 180o Spin Echo EPI, both with and without parallel imaging (ASSET factor of 2 on GE), matrix size of 128 vs 64. Sequences were compared based on fiber statistics, including # and average length of fibers, SD of Trace and Fractional anisotropy. For all, 24cm FOV, 5mm Thk, Contiguous, 24 Slices, 6400~4700ms TR, min Tes, 13 directions, 6 Avgs, 500s/mm2 b-values were used with standard shimming and spatial spectral fat saturation. Typical scan times were 6:44mins. For experiments with force production, matrix size and averages were reduced to 64x64 and 4 Nex. T2-FSE images were also collected for distortion corrections, with the same slice locations, thicknesses and TE. DTI images were collected with the foot at 90o (relaxed), +20o plantar-flexed, and 7o dorsi-flexed. Susceptibility induced and eddy current distortions were corrected using a free form optical flow algorithm using the T2-FSE images as reference. Fibers were tracked using DTIStudio [2] with a fractional anisotropy threshold set at 0.8~0.15. Fibers were examined in similar regions of interest in the relaxed, plantar-flexed (PF) and dorsi-flexed (DF) positions. Fiber lengths, mean fiber ADC and FA values were calculated for the selected regions of interest. Pennation angles were determined from a custom-built software that created a 3D surface map of the aponeurosis tracked on the T2-FSE images and the pennation angle at any fiber location was calculated as the angle between the tangent to the aponeurosis surface and the leading eigenvector.

Results and Discussions: The optimal sequence was the spin echo EPI with a matrix size of 128, acceleration of 2, with a TE of 48ms. The distortion correction algorithm corrected both the susceptibility and the eddy current distortions. Fig. 1 shows the fibers in the medial gastrocs and the soleus. An increase in length and decrease in pennation angle was seen going from plnatorflexion to rest to dorsiflexions. Large pennation angle changes with PF is seen in the soleus. $\lambda 3$ and fractional anisotropy in the three states (Fig. 2) show that $\lambda 3$ increases and FA decreases on plantorflexion. Since $\lambda 3$ has been postulated as proportional to fiber diameter, this translates to increase in fiber diameter with PF. The 3D surface fit of the aponeurosis is shown on the left of Fig. 3 as a red mesh diagram, with a MG fiber shown pennated to the aponeurosis in violet on the right. The estimation of the pennation angle is done from this. The Table shows as example, the length and pinnation angle for the Sol and MG muscle at Rest, PF and DF, and clearly shows increase in angle during PF in MG and Sol, while length decreases. The anisotropy factor which is proportional to the thickness of the fiber can be seen to be increasing during plantar flexion both in soleus and MG. Similarly these parameters could be measured and compared in dorsi flexion.

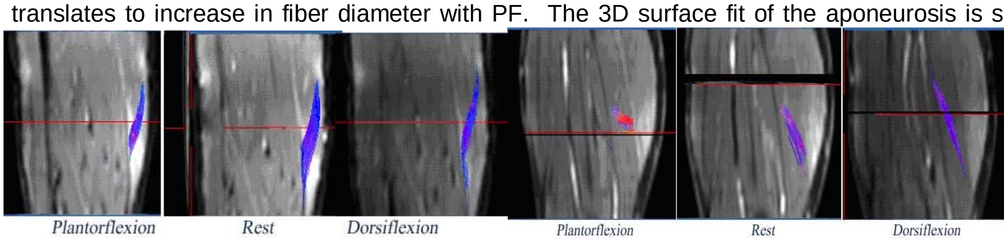
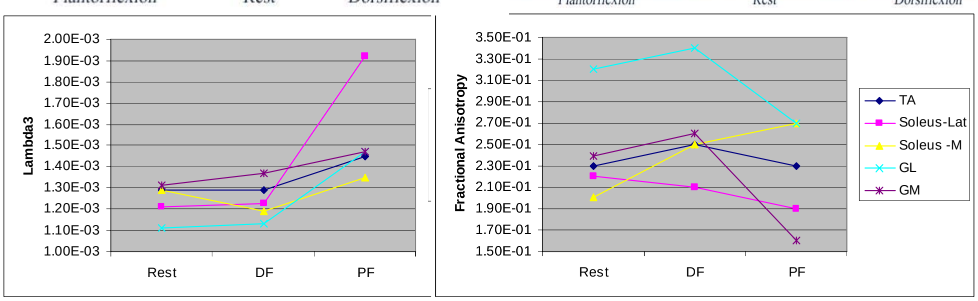


Figure 1: Fibers tracked from the same ROI in plantorflexion, rest, and dorsiflexion in the medial gastrocs (left) and in the soleus (right).

Figure 2: $\lambda 3$ and Fractional anisotropy for different muscle groups in the three states.



<table>
<tr><th rowspan="2">Index</th><th colspan="3">Medial Gastrocs</th><th colspan="3">Soleus</th></tr>
<tr><th>Rest</th><th>Plantar Flexed</th><th>Dorsi Flexed</th><th>Rest</th><th>Plantar Flexed</th><th>Dorsi Flexed</th></tr>
<tr><td>Length</td><td>53±2</td><td>49±2.5</td><td>57±1.5</td><td>45±3</td><td>30±4.1</td><td>55±1.7</td></tr>
<tr><td>Pinnation Angle</td><td>20+2.5</td><td>30±3.5</td><td>18±1.5</td><td>30±3</td><td>50±2</td><td>27±3</td></tr>
<tr><td>Anisotropy (λ_3)</td><td>0.14±0.02</td><td>0.25±0.04</td><td>0.13±.02</td><td>0.12±0.02</td><td>0.20±0.04</td><td>0.07±0.03</td></tr>
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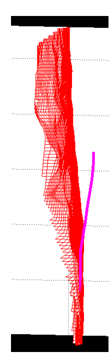

Conclusions: Fibers tracked using DTI could be visualized well with the lower leg at rest, flexed and in active conditions. The changes in pennation angle and fiber angles are in concurrence with previous work by Magnaris.