Evidence of 3-D Fabric Structure in Skeletal Muscle via in-Vivo DTI and Eigenspace Reconstruction

D. Chen[1], D. C. Karampinos[1,2], A. Gharibans[1], K. F. King[3], and J. G. Georgiadis[1,2]

[1]Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, United States, [2]Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, IL, United States, [3]GE Healthcare, Waukesha, WI, United States

Introduction: The established difference between the secondary and tertiary eigenvalues of the diffusion tensor in skeletal muscle [1] hints of the presence of anisotropic diffusion in the transverse direction (i.e. normal to the local fiber). DTI MRI has been employed successfully to reconstruct the fiber tracts in the human tibialis anterior [2], and its potential to elucidate additional structure has been recognized [3]. Towards this end, a candidate model of the muscle as a composite medium was proposed [4], based on the simplification that the myofibers have elliptical cross-sections and the major axis of the ellipse is aligned with the secondary eigenvector. Ultramicroscopy of skeletal muscle has revealed a complex architecture with the muscle fibers tethered by crisscrossing perimysium fibers aligned at ±45° relative to the fiber axis [5]. There is also strong and growing evidence that the strain along skeletal muscle fibers is non-uniform [6,7], indicating the presence of a complex 3-D network of active and passive elements and the transmission of stress perpendicular to the fiber direction. The transverse stress is consistent with the alignment of the complex network of intramyocellular (sarcolemma, sarcoplasmic reticulum, etc) and extramyocellular (interfiber matrix and aponeuroses) restrictions to diffusion. High angular resolution diffusion imaging experiments on human calf muscle verified the asymmetry of the skeletal muscle diffusion on the transverse plane, and provided evidence that the orientation of the secondary eigenvector is spatially coherent and consistent with muscle anatomy in individual axial calf slices [8]. By considering multiple slices and reconstructing the primary and secondary eigenspaces, our aim here is to examine the behavior of the secondary eigenvector field in 3-D.

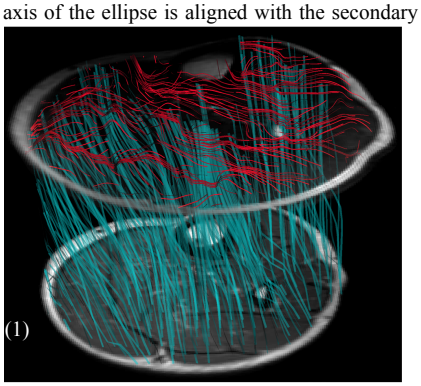
Materials and Methods

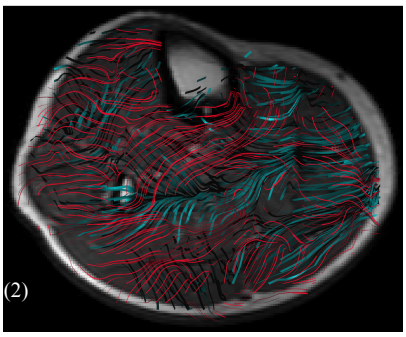
In vivo measurements: The MR measurements were performed on a 3 T full-body GE scanner (General Electric Healthcare, Waukesha, WI). A single-channel lower extremity coil was used to scan the right calf of a healthy male volunteer lying supine at rest. Diffusion-weighted images were acquired using a single-shot diffusion weighted stimulated-echo EPI sequence with the following parameters: TR/TE = 2000/52 ms, FOV = 20 cm, slice thickness = 10 mm, acquisition matrix = 64×40 (5/8 partial phase encoding), and N_{ex}=6. Diffusion-weighted gradients were applied along 30 non-collinear directions with a nominal b-value of 541 s/mm^2. The diffusion-encoding parameters were: δ = 15 ms, Δ = 40 ms, g_{max} = 30 mT/m. Six axial slices were acquired with the imaging volume centered on the widest cross section of the calf muscle, and fat suppression was performed using a spatial-spectral RF pulse.

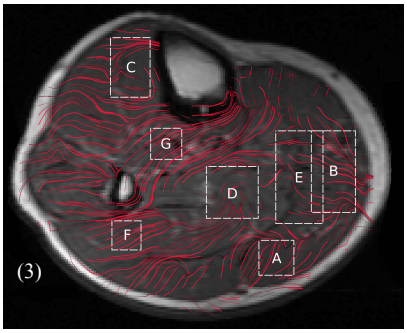
Eigenspace Reconstruction & Representation: The DTI model is first used to compute the diffusion tensor eigenvalues (λ_1, λ_2, λ_3) and eigenspace (spanned by the eigenvectors $\mathbf{V_1}$, $\mathbf{V_2}$, $\mathbf{V_3}$). We then compute the first two principal components of the diffusion flux by forming the products $\lambda_1\mathbf{V_1}$ and $\lambda_2\mathbf{V_2}$ on a voxel-by-voxel basis, and then employ 3-D streamline visualization (Amira®, Visage Imaging Inc., San Diego, CA) to reconstruct and render the flow of these two vector fields. Care has to be taken to assign a direction for each eigenvector consistently so the streamlines (smooth curves tangential to each vector) can be defined. Finally, we use the change in angle ($\Delta\mathbf{V}_2$) of $\mathbf{V_2}$ among pairs of voxels in each column normal to the slice, as a simple quantitative metric to assess the degree of coherence in the proximodistal direction. Given the 6 slices, each column contains 5 $\Delta\mathbf{V}_2$ values.

Results and Discussion:

Fig. 1 depicts the flow streamlines of the primary eigenspace ($\lambda_1\mathbf{V_1}$) as blue ribbons between the proximal (top) and distal (bottom) anatomical axial images of the calf. For clarity, the flow streamlines of the secondary eigenspace ($\lambda_2\mathbf{V_2}$) are rendered only for the proximal slice, but topologically similar streamline structures appear on all six slices. Figs. 2-3 are distal views of the top slice of Fig. 1, and the ROIs mark several key areas of the calf musculature. The 3-D rendered muscle can be abstracted as a fabric whereby the interfiber matrix acts as a transverse yarn (weft) woven through the myofibers (warp). The fabric model is consistent with both muscle mechanics and diffusion physics: the myofibers and interfiber matrix adapt in response to muscle strain both in the axial and transverse direction, and this adaptation gives rise to structures which restrict diffusion preferentially. Figs. 1 & 2 reveal prominent 3-D fiber structures (primary eigenspace) in the lateral gactrocnemius aponeurosis (area E) and the interior soleus aponeurosis (area D). As Fig. 2 shows, the secondary eigenspace flow is expectedly complex (tangled) in these areas. In contrast, the secondary eigenspace flow in the remaining ROIs appears more coherent. A two factor ANOVA statistical analysis is performed to examine the spatial distribution of $\Delta\mathbf{V}_2$. The findings for the mean value of $\Delta\mathbf{V}_2$ are as follows: it does not vary significantly in the transverse and proximodistal directions in areas A and F; it does not vary significantly in the proximodistal direction in areas B, C and G; and it varies significantly in both directions in areas D and E. Areas A and F exhibit the highest coherence, in agreement with the findings in [4], while the lack of $\Delta\mathbf{V}_2$ coherence in areas D and E can be atributed to the fine 3-D structure of the aponeuroses, and to DTI partial volume and susceptibility effects.







Figures (**1**) 3-D rendering of $\lambda_1\mathbf{V_1}$ (blue) and $\lambda_2\mathbf{V_2}$ (red) flows; (**2**) distal view of top slice; (**3**) distal view with ROIs.

Conclusion: We introduce streamline visualization using the primary and secondary eigenspace flows derived from DTI, not as a replacement of more sophisticated segmented muscle tractography methods [2], but as an alternative technique to explore the interplay of the two vector fields and the connection between transverse diffusion anisotropy and skeletal muscle architecture. Quantitative results based on simple proximodistal variation of the second eigenvector angle are promising in muscle areas where the fiber structure is topologically simple and devoid of aponeuroses. In order for the proposed fabric model of skeletal muscle to lead to improved models of muscle mechanics, more sophisticated representation of the DTI eigenspace flows coupled with increased DTI spatial resolution is required.

References: [1] Schwenzer NF et al., NMR Biomed DOI: 10.1002/nbm.1409, 2009; [2] Heemskerk AM et al., Magn Reson Med 61, 467-472, 2009; [3] Heemskerk AM and Damon BM, Cur Med Imag Rev 3, 152-160, 2007; [4] Karampinos DC et al., Ann Biomed Eng DOI: 10.1007/s10439-009-9783-1, 2009, [5] Passerieux E. et al. J Struct Biol 154: 206-216, 2006; [6] Kinugasa R et al., J Appl Physiol 105, 1276-1284, 2009; [7] Shin DD et al., J Appl Physiol 107, 1276-1284, 2009. [8] Karampinos DC et al., ISMRM 2009, p. 1928.