Optimization of In Vivo Diffusion Tensor Imaging of Muscles of the Human Lower Leg: Application to Fiber Tracking under Plantarflexed Conditions of the Foot.

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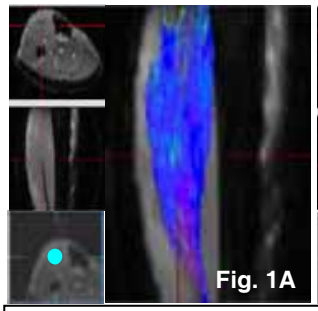
Introduction: Some biomechanical models, particularly in small animals, are able to predict force production from a muscle from the physiological cross-sectional area (PCSA), which is proportional to the ratio of muscle volume to fiber length, modulated by the cosine of the pennation angle. However, these do not extrapolate accurately to larger animal models such as humans. Therefore, it is important to be able to directly measure these muscle architectural parameters in vivo in humans, both in rest and under passive and active conditions for the correct modeling of the musculoskeletal system. Diffusion tensor imaging (DTI) has the potential to non-invasively determine these fiber parameters. Our objectives were (i) to optimize DTI for lower leg muscle imaging exploring parallel acquisition, number of diffusion gradient directions, and large FOV coils for whole leg imaging and (ii) to apply the optimized DTI sequence to monitor muscle fiber changes under passive plantarflexion.

Material and Method: DTI images were acquired on a Siemens 3T scanner with an extremity phased array coil with a fat suppressed single shot EPI sequence employing a dual 180° pulse (to decrease eddy current effects of the diffusion gradients) with a b-value of 600 s/mm^2. The sequences were: (i) TE/TR/FOV/Matrix::69ms/3300ms/{200 x 165}/{128 x 128}. A total of 25 slices were acquired contiguously, with 16 repeats of the acquisition. (ii) The same sequence as above with parallel acquisition (GRAPPA, acceleration factor 2); (iii) and (iv) same sequence as (i) and (ii) respectively but with 12 diffusion gradient sensitization (the averages were cut to 8 to have the same scan time); and (v) using a customized 8-channel phased array coil (Millenium MRI, NY) with a large S/I field of view.

The optimized DTI sequence was then used to image 5 volunteers with leg in a rest and plantarflexed state. A MR compatible foot-pedal device allowed the foot to be stabilized in plantar- and dorsi-flexed states to minimize motion during the DTI scan. Images were acquired axially to cover 12.5 cm length. Fibers were tracked from different muscle compartments for images acquired in the rest and plantarflexed states. Care was taken to position the seed region of interests for fiber tracking in nearly identical locations for both states of the leg. Fibers were tracked using software from http://www.ut-radiology.umin.jp/people/masutani/dTV.htm.

Result and Discussion: The summarized results of the optimization are: (i) DTI images acquired with parallel acquisition had a lower SNR than the images acquired without parallel acquisition. This is a consequence of the √2 decrease from the reduction factor of 2. However, the gain in TE possible with parallel reconstruction in single shot EPI was not sufficient to offset the decrease in SNR. This was due to the fact that for the current choice of a rectangular FOV, 6/8 Fourier acquisition, the decrease in TE was not significant. The gain in SNR (exp{- ΔTE/T2}, with 31 ms for T2 of muscle) for the TE change of 8 ms obtained with parallel imaging is ~1.15, less than the √2*(1.41) decrease in SNR. (ii) Increasing to 12 diffusion gradient directions increased the minimum TE possible for the sequence, with the resulting SNR of the images lower than the corresponding 6 direction images. (iii) The customized coil allowed a large field of view but image quality was affected away from the magnet center. It allowed better tracking from fibers since there was no misregistration artifact from different axial sets. The customized coil was therefore effective in imaging contiguous sections of the extremity placed successively at the magnet center without the need for changing coil placement. Sequence (i) was used for the rest of the DTI imaging as it provided the best SNR among the sequences investigated here.

Fig. 1A shows typical images of fibers tracked at rest and Fig. 1B, for plantarflexed state, in the tibialis anterior muscle compartment. Fig. 2 A and B show similar images at rest and plantarflexed conditions for the soleus and gastrocnemius. The format for each figure shows the two orthogonal projections (left column) with the 3D volume in the main frame with the muscle fibers overlaid on it. The fiber color represents the direction (blue: SI, red: LR, green: AP). A blue region of interest (filled) is shown in the left lower most inset of each figure. This ROI was the seed region for the muscle fiber tracking. For Fig. 1 the ROI was placed on the axial and for Fig. 2, the ROI was placed on the coronal image. The termination condition for fibers was either a baseline voxel with signal intensity below a specified threshold or a fractional anisotropy less 0.18.



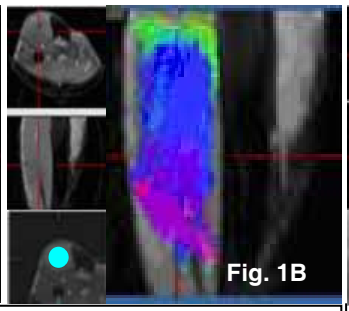
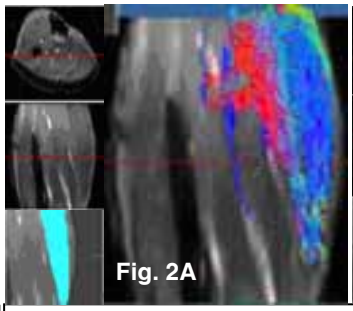


Fig. 1: Fibers tracked from the Tibialis Anterior clearly show SI direction starting from the aponeurosis (left). Some LR component at the aponeurosis is present (purple color). During plantarflexion (right), there is complex rotation of the TA muscles with stronger LR component and



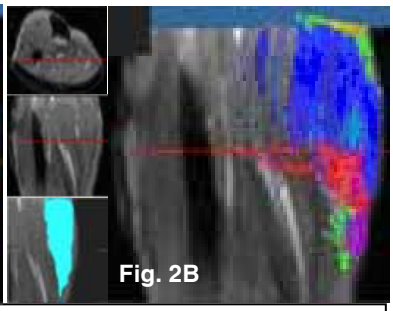


Fig. 2: Fibers tracked from the soleus and gatrocs at rest show the primarily SI component of the gastrocs and the LR direction of the soleus (a). During plantarflexion, the most striking change is the LR direction of the soleus now clearly has a SI direction.

Conclusion: It is feasible to monitor the changes in fiber directions that occur on plantarflexion. There appears to be complex changes in muscle fiber directions in all the major muscle compartments. This could potentially be used to monitor changes in fiber length and pennation angle non-invasively for different extremity positions and under passive and active conditions. The results should be very effective inputs for Finite Element Modeling of the musculoskeletal system.