# *In Vivo* Diffusion Tensor Imaging of Human Thigh Muscles at 3.0 Tesla

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**Introduction**: Diffusion tensor magnetic resonance imaging (DT-MRI) has been widely applied in tissues with ordered, elongated structures (e.g., brain, heart, and skeletal muscle) to assay the anisotropic diffusion behavior of water molecules. By measuring water diffusion in different directions and fitting the observed signals to a tensor model [1], the derived quantitative indices, such as fractional anisotropy (FA), apparent diffusion coefficient (ADC), and the primary eigenvector, provide information about tissue structure and orientation at a microscopic level. Although muscle fibers exhibit highly ordered structure, DT-MRI study in skeletal muscle is limited by short $T_2$ values and $B_0$ and $B_1$ inhomogeneity, especially at high field strengths. DT-MRI has been validated [2] and applied in an animal inflammatory model [3]. *In vivo* human studies have also been performed at 1.5 T [4,5], and the repeatability of DT-MRI has been assessed in human leg muscles [6,7] at 3.0 T. However, no systematic study of DT-MRI indices from the normal human thigh muscles has been reported at 3.0 T. This has particular significance because of the proximal-to-distal presentation of many neuromuscular disorders, causing the thigh muscles to be an early site of pathology. In this work, DT-MRI in thigh muscles was performed in order to investigate the normal values obtained by, and the repeatability of, this technique.

**Methods**: *Subjects*: Nine healthy subjects (four males) participated in this study. Six subjects have been imaged twice at an average of 35 days following the first visit. The subjects lay supine in a feet-first position. All subjects have 48-hour restrictions to dietary, exercise, and non-prescription medication. *Data acquisition*: Data were collected on a 3.0-T Philips Achieva MR scanner, with a two-channel body coil for excitation and a six-channel SENSE cardiac coil for signal reception. Images were acquired at the center of right thigh in foot-head direction. The DT images have in-plane resolution of $2 \times 2$ mm$^2$ and slice thickness of 7 mm. Other sequence parameters include: TR = 4000 ms, TE = 48 ms, SENSE factor = 1.5, *b*-value = 450 s·mm$^{-2}$ in 15 diffusion-weighted directions (and one $b = 0$ image), and single-shot spin-echo echo-planar imaging (EPI) readout. Fat signal suppression was implemented by using a gradient reversal off resonance suppression technique and a saturation pulse on the olefinic proton resonance. High-resolution $T_1$-weighted images were acquired to provide anatomical reference. *Data analysis*: All diffusion-weighted images were registered to the $b = 0$ images using an affine transformation algorithm. The data were then fitted to a tensor model [1]. To evaluate the DTI parameters in single muscles, region-of-interests (ROI) were drawn along the boundary of each muscle and pixels affected by partial volume, motion and flowing artifacts were excluded. Bland-Altman plots of the difference vs. mean value of each parameter from two measurements evaluated the repeatability. A two-tailed paired Student's *t*-test between the two measurements was performed and the probabilities were calculated ($p<0.05$ was considered significant).

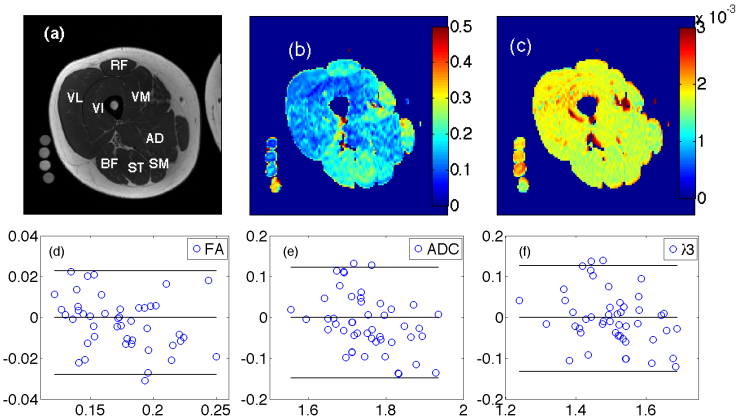


Figure 1. High-resolution T1w (a); FA map (b); ADC map (c); and Bland-Altman plots of FA (d), ADC (e), and $\lambda_3$ (f).

**Results and Discussion**: Figure 1a) shows an example anatomical image of a male subject, with eight muscles labeled (AD: adductor magnus; BF: biceps femoris, long head; RF: rectus femoris; SM: semimembranosus; ST: semitendinosus; VI: vastus intermedius; VL: vastus lateralis; VM: vastus medialis;). Figure 1b) and 1c) show example FA and ADC maps, respectively. The mean and standard deviation values of DTI indices, FA, ADC, and eigenvalues, $\lambda_1$, $\lambda_2$, and $\lambda_3$ of the eight muscles from the first measurement in the nine subjects are listed in Table 1. Across all subjects, consistent DTI indices have been obtained for all muscles. No significant difference was observed between subjects with different genders. The Bland-Altman plots of FA, ADC and $\lambda_3$ are shown in Figure 1d-f). Across all muscles, the repeatability coefficients (RC) of FA, ADC, $\lambda_1$, $\lambda_2$, and $\lambda_3$ were 0.03, 0.14, 0.17, 0.16, and 0.13, respectively. None of the comparisons of the between-day mean values was significant. The DT-MRI indices (Table 1) obtained in this work provide reference values for future studies of exercise induced muscle damage, inflammatory myositis, and longitudinal studies. Fiber tracking will be performed to characterize muscle fiber structure.

Table 1. DTI indices of thigh muscles at 3.0 T. The unit of ADC, $\lambda_1$, $\lambda_2$, and $\lambda_3$ are $10^{-3}$ mm$^2$/s.

| | AD | BF | RF | SM | ST | VI | VL | VM |
|---|---|---|---|---|---|---|---|---|
| **FA** | 0.16(0.01) | 0.20(0.02) | 0.18(0.01) | 0.19(0.01) | 0.23(0.02) | 0.16(0.02) | 0.14(0.02) | 0.15(0.01) |
| **ADC** | 1.72(0.04) | 1.67(0.06) | 1.76(0.06) | 1.75(0.07) | 1.68(0.06) | 1.84(0.07) | 1.91(0.11) | 1.76(0.03) |
| **$\lambda_1$** | 2.01(0.04) | 2.06(0.05) | 2.10(0.06) | 2.12(0.08) | 2.12(0.07) | 2.15(0.07) | 2.19(0.13) | 2.05(0.03) |
| **$\lambda_2$** | 1.64(0.05) | 1.55(0.07) | 1.66(0.07) | 1.63(0.09) | 1.53(0.06) | 1.78(0.09) | 1.90(0.17) | 1.69(0.06) |
| **$\lambda_3$** | 1.50(0.04) | 1.41(0.08) | 1.51(0.05) | 1.49(0.05) | 1.38(0.08) | 1.59(0.06) | 1.65(0.06) | 1.54(0.03) |

**References**: [1] Basser PJ et al, *Biophys J*, 66:259 (1994); [2] Damon BM et al, *MRM*, 48:97 (2002); [3] Bryant ND et al, *Proc ISMRM 20*:1442 (2012); [4] Qi J et al, *JMRI*, 27:212 (2008); [5] Kermarrec E et al, *AJR Am J Roentgeno*, 195: W352 (2010); [6] Heemskerk AM et al, *MRM*, 61:467 (2009); [7] Heemskerk AM et al, *NMR Biomed*, 23:294 (2010).