Specific changes in water diffusivity due to passive shortening and lengthening of the thigh muscles – A Diffusion Tensor Imaging study

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Introduction

The organization of skeletal muscle fibers, or muscle architecture, strongly determines the muscle's maximum force capacity [1]. Diffusion tensor imaging (DTI), widely used in brain studies, has recently emerged as an attractive tool for investigating the microstructure of skeletal muscle. In this latter, DTI provides information about the water molecules self-diffusion which is restricted by physical barriers such as membranes, cytoskeleton and cellular organelles i.e. mitochondria and sarcoplasmic reticulum [2]. Considering skeletal muscle as a network of parallel and elongated fibers, longitudinal water diffusion is facilitated as compared to diffusion in radial directions. Recent studies performed in the human calf muscle [3, 4] have investigated the effects of passive muscle length changes on diffusion properties and shown an increase in mean diffusivity with muscle shortening. So far, this muscle length (or joint angle) dependence of diffusivity has however never been investigated in human thigh muscles, for which only few DTI studies [5, 6] have been carried out. The investigation of thigh muscles organization is of interest given that their architecture might be largely affected in neuromuscular disorders [7]. The present study investigated whether the DTI metrics were sensitive enough to structural muscle fiber changes induced by both passive shortening and lengthening of the thigh muscles.

Methods

Eight healthy male subjects (age: 34 ± 6 yrs) were examined in a 1.5T whole-body MRI scanner (Magnetom Avanto, Siemens Healthcare, Erlangen, Germany) with a flexible 16-channel phased-array coil. Subjects were placed in a prone position within the magnet with the receiver coil positioned around the right thigh. Images were recorded from the mid-thigh region with the knee joint positioned at 0° (i.e., full extension) and at 45° in a random order. The foot was raised and placed on an adjustable MRI-compatible device in order to sustain the resting knee position at 45°. To ensure a stable position and to avoid knee motion during MRI acquisitions, subjects were firmly fixed to the bed of the magnet with two rigid straps positioned over the leg and the hip. A spin-echo single-shot diffusion-weighted EPI sequence with a frequency-selective fat saturation (SPAIR) was used. The diffusion-weighted images were acquired with the following parameters: TR/TE= 5000/53 ms; BW = 2004 Hz/px; FOV = 200 × 200 mm²; matrix size = 96 × 96; slice thickness 5 mm; 31 slices; 6 averages; b values = 0 and 400 s/mm²; 12 directions; acquisition time = 6 min 47 s. Parametric maps of eigenvalues (λ_1, λ_2 and λ_3), fractional anisotropy (FA) and mean diffusivity ($<\lambda>$) were generated using DTI-Tool software (www.trackvis.org). For each subject, ROIs were manually drawn on six non-contiguous slices in the vastus lateralis (VL), rectus femoris (RF) and biceps femoris (BF) muscles and the resulting DTI metrics were averaged for each muscle. Care was taken to avoid large vessels and partially suppressed subcutaneous fat. For accurate anatomic delineation, high resolution T_2-weighted spin-echo images were additionally acquired (see Figure 1) with the following parameters: TR = 3671 ms; TE = 9.8 ms; BW = 227 Hz/px; FOV = 233 × 182 mm²; matrix size = 256 × 256; slice thickness = 5 mm; 11 slices; 1 average. Unpaired *t*-tests were used to compare DTI metric values between the two testing conditions for each muscle.

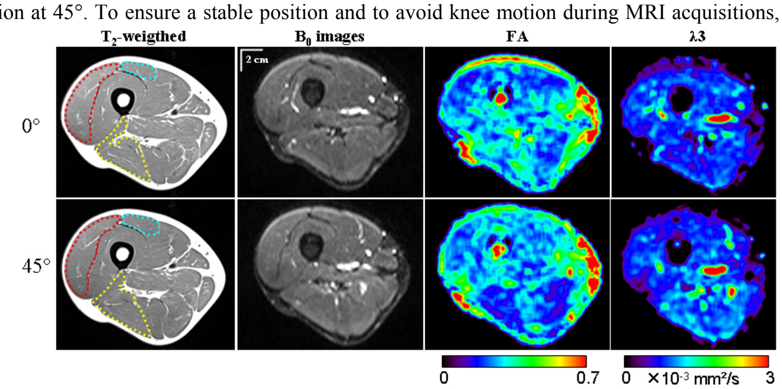

Figure 1 *– T_2-weighted images, B_0 images, FA and λ3 maps obtained at two different knee joint angles (i.e., 0° and 45°) for a representative subject. ROIs drawn in red, cyan and yellow correspond to the vastus lateralis, rectus femoris and biceps femoris muscles, respectively.*

Results

The vastus lateralis muscle showed a significant increase in FA (+ 7%) and a decrease in the eigenvalue λ_3 (- 3%) with muscle lengthening whereas the others parameters were similar between the two positions (Figure 1 & Table 1). In contrast, a decrease in FA (- 8%) and an increase in $<\lambda>$ (+ 3%), λ_2 (+ 4%) and λ_3 (+ 7%) were observed in the shortened biceps femoris muscle. Surprisingly, all the DTI metrics remained unchanged in the rectus femoris muscle when the knee joint angle was modified.

	0°			45°		
	VL	**RF**	**BF**	**VL**	**RF**	**BF**
FA	0.27 ± 0.01	0.29 ± 0.02	0.30 ± 0.01	0.29 ± 0.02	0.30 ± 0.02	0.28 ± 0.01
$<\lambda>$	1.62 ± 0.06	1.60 ± 0.08	1.59 ± 0.04	1.61 ± 0.05	1.60 ± 0.06	1.64 ± 0.03
λ_1	2.08 ± 0.08	2.09 ± 0.07	2.09 ± 0.06	2.10 ± 0.08	2.11 ± 0.05	2.11 ± 0.04
λ_2	1.58 ± 0.06	1.55 ± 0.08	1.54 ± 0.05	1.56 ± 0.05	1.55 ± 0.07	1.60 ± 0.04
λ_3	1.20 ± 0.04	1.16 ± 0.08	1.13 ± 0.03	1.16 ± 0.03	1.16 ± 0.07	1.21 ± 0.03

Table 1 *– $<\lambda>$, λ_1, λ_2 and λ_3 are expressed in 10^{-3} mm²/s. Underlined data are significantly different from 0° (P< 0.05).*

Discussion

Previous studies [3, 4] have reported variations in diffusion properties of the calf muscles according to the ankle joint angle and found an opposite behaviour between the agonist and antagonist muscles. In the present study, similar changes were observed for the BF and the VL muscles whereas the DTI metrics of RF muscle were kept constant suggesting muscle-dependent changes in water diffusivity during passive shortening and lengthening of the thigh muscles. Although the exact meaning of the second and the third eigenvalues is still unclear, it has been suggested that λ_2 and λ_3 would illustrate the diffusive transport within the endomysium perpendicular to the long axes of the muscle fibers and within the cross-section of a muscle fiber [8], respectively. The specific variations observed within the knee extensors and between the BF and the RF muscles in water diffusivity could be ascribed to heterogeneous microstructure changes among the thigh muscles. Interestingly, it has been demonstrated that muscle shortening was nonuniform and lesser in regions containing aponeurosis tissues, therefore underlying that the features of muscle architecture could affect the mechanical behaviour of muscle fibers [9]. The muscle fibers of the RF muscle originate from two long aponeuroses and follow three-dimensional trajectories [10], suggesting that muscle shortening was likely lowered by the aponeuroses. We hypothesized that changes in water diffusivity observed in this study, reflect nonuniform microstructure changes among the thigh muscles due to their complex muscle-tendon architectures.

References

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