Quantitative MRI as an indirect evaluation tool of the mechanical properties of muscles

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INTRODUCTION

Muscles generate forces to move or stabilize human body segments. Their structure is made of active fibers and passive connective tissues. Muscles mechanical properties are separated in active tension, which is created by the fibers contraction, and passive tension, the muscle resistance to stretching. Those mechanical properties are affected by many pathologies. Some affect them directly like the Duchenne muscular dystrophy, which creates an infiltration of collagen and fat tissues in the muscle. Other pathologies affect muscles indirectly. For example, an idiopathic scoliosis patient will have a three-dimensional deformation spine which will disrupt the symmetry of the loads and the properties of the dorsal muscles. Several specific magnetic resonance imaging (MRI) techniques were developed for muscles applications, such as MR spectroscopy to quantify adenosine-5 triphosphate, lactates or creatine [1], MR elastography for the visualization and the measure of deformation waves within the tissue submitted to mechanical excitations and to assess their mechanical properties [2], diffusion anisotropy for the spatial architecture [3] and T2 mapping for muscular activity [4]. It is well established that MR parameters obtained by quantitative magnetic resonance imaging (qMRI) are linked to the mechanical properties and to the biochemical composition of cartilages and intervertebral discs. From those studies, we hypothesise that a relationship exists between the mechanical properties and the MR parameters of muscles. The aim of this study is to develop an indirect evaluation tool of the mechanical properties of degenerated muscles using qMRI.

METHODS

The semi-membranous, rectus femoris, tibialis anterior, meditriceps, anterior trapezius and levator scapulae ventralis muscles of three adult rabbits were dissected [5][6], and separated into two groups. The first group was tested 12 hours post mortem, in a state of rigor mortis while the second group was tested 72 hours post mortem in a state of post-rigor mortis [7]. The tests consisted of a qMRI acquisition and a tensile test. For the qMRI acquisition, the muscles were clamped in two grips and placed in an MRI-compatible apparatus at their initial length. qMRI was carried out using a 3T whole-body apparatus (Philips Achieva X-Series). A single slice, 3mm thick, was taken in the coronal plane. The relaxation times were determined by using a multiple inversion-recovery turbo spin-echo sequence for T1, and, respectively, spin-echo and gradient-echo sequences with multiple echo times for T2 and T2*. The diffusion tensor was extracted from spin-echo EPI diffusion-weighted sequence, with 15 non-collinear diffusion encoding directions. The MT images were obtained using a gradient echo sequence with and without a magnetization transfer saturation pulse. The MRI analysis was performed using an in-house program (Matlab, The MathWorks Inc.). T1, T2, T2*, Apparent Diffusion Coefficient (ADC) and Fractional Anisotropy (FA) were extracted from the signal intensity by non-linear regressions to their respective signal expressions. For the tensile test, the muscles were cut into sample of 10x40x10mm (W*L*H). Samples were clamped in two grips and placed in a micro-mechanical testing system. (Mach-1, Biomomentum Inc.). Then, a uniaxial tensile test until failure was performed with a constant speed of 1mm/s. The Young's modulus E was calculated from the slope of the force-displacement curve in the linear part. Correlations tests and multilinear regressions were investigated between the mechanical properties and the MR parameters (SigmaPlot, Systat Software,Inc.).

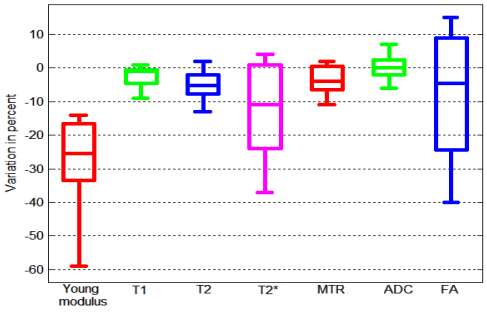

Figure 1: Variation of the Young modulus and the MR parameters when the muscle go from a state of rigor mortis to a state of post-rigor mortis.

RESULTS

Eighteen muscles have been studied, (two set of legs and one set of arms.) Figure 1 shows the dispersion of the variation Δ of the mean of E, T1, T2, T2*, MTR, ADC and FA when the muscle goes from a state of rigor mortis to a state of post-rigor mortis. Significant differences exists between rigor and post-rigor mortis for E ($p<0.001$), T1 ($p=0.02$), T2 ($p=0.01$) and MTR ($p=0.10$) but not for T2* ($p=0.56$), ADC ($p=0.85$) and FA ($p=0.34$). The Spearman rank order correlation test indicated a significant relationship between E and MTR ($r=-0.58$, $p=0.02$), between ΔE and ΔT2 ($r=-0.86$, $p=0.002$), and between ΔE and ΔMTR ($r=0.75$, $p=0.04$). A multiple linear regression ($R^2=0.54$) exist between E, MTR ($p=0,009$) and ADC (0,018), and also between ΔE, ΔT2 ($p=0.02$) and ΔMTR (0.02).

$$E\,[Pa] = (52{,}2\,[Pa] - 50{,}2\,[Pa] \times MTR\,[\%]) \times 10^4 - 200{,}7\,[Kg/s*m^3] \times ADC[m^2/s]$$

$$\Delta E = -0.292 - 1.96\Delta T2 + 2.486\Delta MTR$$

DISCUSSION

The data obtained for both mechanical and MRI properties correspond to the values reported in the literature. The variation of tension between rigor mortis and post-rigor mortis comes from the degradation of myosin and actin. This degradation affects the structure, the chemical environment and the water retention capacity. These three parameters are known to affect the MR parameters. The results indicate a significant relationship between E, MTR and ADC. The Young's modulus of muscles, i.e. the passive mechanical behaviour of muscles, can be evaluated indirectly from quantitative MRI using magnetization transfer and diffusion tensor acquisitions.

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