Passive stretch of muscle fibers measured in vivo using a novel MRI diffusion tensor imaging based approach

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INTRODUCTION: One of the main future directions in medicine is tailoring therapies and treatments to meet the specific demands of the patients. One such development within the orthopaedic-biomechanics field is the development of patient specific models[1]. For the accuracy of these biomechanical models, detailed information on muscle architecture is of vital importance. Muscle architecture is defined as the physical arrangement of muscle fibers at the macroscopic level that determines a muscle's mechanical function. So far most modeling studies use architectural parameters obtained from cadavers, and are therefore not patient specific. Although ultrasound can be used to obtain muscle architecture to some extent and it is fast and easy to use, it is limited to superficial muscles and offers mostly 2D measurements, while muscle architecture has a complex 3D geometry. These limitations can be overcome with MRI and specifically Diffusion Tensor Imaging (DTI). DTI enables a reproducible and validated 3D visualization of the muscle fibers [2]. However, DTI requires that muscles and tendons are segmented separately, in order to avoid overestimation of muscle fiber lengths. Despite the strength of the DTI technique, its applicability is hindered by the necessary intensive manual work. In this work we introduce a new analysis method for muscle DTI which enables fast and accurate fiberlength estimations. The novelty of our method is the automatic segmentation of tendons from the muscle fiber tracts based on the fiber tract density. The technique relies on the notion that DTI is capable of tracking fibers in muscle as well as in tendons. Muscle fibers run parallel and do not converge, which implies a constant fiber tract density over the muscle length. However, at the sites where muscles connect to a tendon or aponeurosis the tract density abruptly changes which offer a way to distinguish muscle from tendons based on their quantitative tract density values. Furthermore we show that this new technique is capable of quantifying muscle fiber length changes due to passive stretch and compression in the human lower leg.

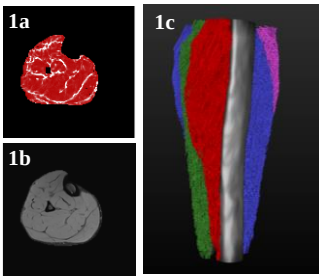

***Figure**: **1a)** Tendon location derived from density of fibers. White represents high fiber density, and is associated to tendons. Anatomical image is presented for visual comparison in figure **1b**, where tendons are hypointense. **1c)** Fiber tracks obtained from the DTI data, showing the complex 3D geometry of the muscles in the lower lea.*

METHODS: 5 healthy male volunteers (mean age = 27 years, mean BMI = 22) were scanned with a 3T Achieva MRI scanner (Philips). A custom built device was used to fixate the foot in different positions. Measurements of the calf were performed for 3 different passive foot positions: 15° dorsiflexion, neutral position and 30° plantarflexion. The measurements included a Dixon scan to be used as anatomical reference and a DTI scan (b=400 s/mm^2, 15 diffusion encoding directions). The total scan time was 33 minutes per subject (11 minutes per position). The muscle groups in the lower leg were manually segmented in the Dixon scan. Radial diffusivity was determined from the DTI data and expressed as mean over each muscle and then averaged over all volunteers. Fiber tractography was performed for 4 muscle groups: Tibialis Anterior (TA), Extensor Digitorum Longus (EDL), Soleus (SOL) and Gastrocnemius Medialis (GCM). Fiber tractography was performed twice for each muscle. In the first fiber tractography, higher density of tracts is observed in the location where tendons are (figure 1a and 1b). By running the tractography algorithm a second time, and excluding areas with higher tract density, it is possible to exclude tendon volume and thus obtain more reliable muscle fiberlength estimation. For each reconstructed fiber, fiber lengths were extracted and the mean values were calculated over all subjects.

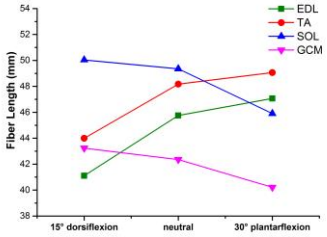

***Figure 2:** Fiber length in mm in 4 muscles in the lower leg (Tibialis Anterior, Extensor Digitorum Longus, Soleus and Gastrocnemius Medialis) for 3 different passive positions of the foot (15° dorsiflexion, neutral position and 30° plantarflexion).*

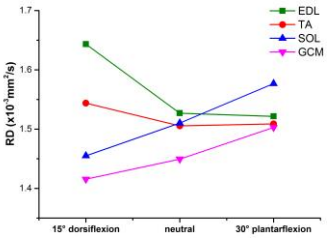

***Figure 3:** Radial Diffusivity for the same muscle groups shown in figure 2.*

RESULTS: Average fiber length of 4 muscles (extensor digitorum longus, tibialis anterior, soleus and gastrocnemius medialis) are showed in figure 2 as a function of different foot positions. The anterior muscles EDL and TA, which are responsible for dorsiflexion of the foot, are seen to shorten in dorsiflexion whit respect to the neutral foot position. On the other hand the soleus and gastrocnemius medialis muscles, which play a major role in plantarflexion, show reduced fiber length in the plantarflexed position. The radial diffusivity, which indicates the diffusion of water molecules in the direction perpendicular to the axis of the fiber shows an opposite trend (figure 3) when compared to the changes in fiber length. In fact, increased radial diffusivity is observed in the shortened muscles groups (EDL and TA in dorsiflexion and SOL and GCM in plantarflexion).

DISCUSSION: Our presented method estimated the muscle fiberlengths semi automatically and results are in agreement with the reported values of both cadaveric and ultrasound studies in literature [3]. Furthermore our method was able to detect passive lengthening and shortening of the muscle fibers in relation with the ankle position, without the need to manually segment the tendon. Next to fiberlength measurements, the DTI-derived parameters changed in relation with the ankle position, especially the radial diffusivity (RD), which is associated with fiber diameter. Increase in radial diffusivity with muscle stretching was reported in previous studies [4]. However, using our tendon segmentation method, differences in fiber length due to passive stretching could also be observed in all muscles groups. Our results suggest that when a muscles shortens, the fiber diameter increases in order to maintain a constant volume. Fiberlength is an important parameter of muscle architecture and is therefore vital to implement in patient specific models of muscle functioning. We believe our work can be used to strengthen these models. An important strength of our method is that it also enables accurate visualization of the tendinous structures, potentially enabling automatic measurements of the pennation angles. Pennation angle together with the fiberlength and muscle volume can be used to estimate the maximum force of the muscle.

SIGNIFICANCE: This work shows the possibility of measuring changes in muscle fiber length during passive foot flexion and extension in a completely noninvasive way and in a clinically feasible scan time. Therefore, the workflow provides a novel and promising readout for muscle related research, which can be used in muscle injury diagnostics, treatment optimization of muscle related diseases and in generating personalize biomechanical models and pre-planning tools of patients suffering from diseases of their musculoskeletal system.

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