Functional DTI in Voluntarily Contracted Human Calf Muscles Using an MR Compatible Ergometer

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Introduction Knowledge about the 3D architecture of muscles is important, first, for deeper understanding of contraction dynamics and muscle deformation, and second, as a prerequisite for the development of realistic finite-element muscle models. Diffusion tensor imaging (DTI) provides valuable information about muscle architecture in both normal and diseased states [1]. So far, most DT acquisitions in skeletal muscles relied on SE-EPI sequences, which are used to determine DTI changes in passively moved muscles [1,2]. Recent studies including measurements in voluntarily contracted calf muscles did not use ergometers that provide force or movement monitoring during the exercise and, thus, may be limited by varying muscle performance [3,4]. Therefore, in the present work we introduce an MR compatible ergometer with monitoring and visual feedback options to perform DTI measurements during voluntary muscle contractions at different joint angles. In addition, we employed a pulse sequence for DTI, which is based on a stimulated echo acquisition mode (STEAM) preparation in combination with a FLASH readout [5].

Materials & Methods Functional MR studies were conducted in a clinical 3 T whole-body MR scanner (TIM Trio, Siemens Healthcare, Erlangen, Germany) with a MR compatible ergometer. The latter consists of a pneumatic cylinder with an angle and force sensor for monitoring the volunteer's performance during exercise. MRI acquisitions were repeated at three ankle positions of the right joint ankle: neutral position (0°) and plantar flexions of 10° and 20°, respectively. The volunteers were asked to push the pedal to adjust the requested ankle joint position with the aid of a visual feedback system that included a custom built MATLAB visualisation routine (as shown in Fig. 1, top row) and the Visual Stim Digital system (Resonance Technology Company, Inc., CA, USA) and to hold this position during the MRI measurements. T_2-weighted reference images (ME-TSE sequence, TE = 15, 38, 69 ms, TR = 2 s, TA = 1.5 min, 1×1×2 mm³, 256×184 pixel matrix, 3 slices) were acquired for each ankle position. Due to the known T_2 increase in activated muscles these measurements were used to localize contracted calf muscles during exercise [6]. DTI data sets were acquired with a turbo-STEAM sequence [5]. Four slices were acquired, each 4 mm thick (FoV = 256 mm × 144 mm).

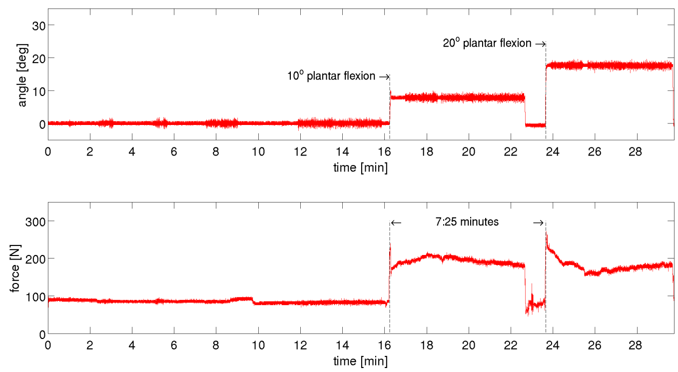

Fig. 1 *Monitoring data acquired during the MRI examinations for three ankle positions in rest (0°) and under load (10° and 20°).*

By using a negative slice distance of -50% effective isotropic resolution of (2.0 mm)³ was achieved for the diffusion tensor data set. Due to the limited duration of the different exercises DTI measurements were repeated only once for each ankle position. Five b_0 and 30 DW images with diffusion weightings in 30 different spatial directions, each with a *b*-value of 600 s/mm², were acquired. Sequence timings were TM/TE/TR = 979/1000/1682 ms, leading to a total measurement time of 3:56 min per ankle position. Tensor reconstruction was performed using the Diffusion Toolkit [7] and the tensor angle θ, defined as the angle between the main tensor direction and the transverse image plane, was calculated with a MATLAB routine. For data analyses three ROIs for the *M. tibialis* (passive muscle), *M. soleus* and *M. gastrocnemius medialis* (contracted muscles during plantar flexion) were selected.

Results Parameter maps of the contracted calf muscles are shown in Figure 2. Table 1 presents mean and SD values of the ROI-based analysis. Significant differences ($p < 0.1$) determined via Students *t*-test between data of for 0°-10° and 0°-20°are marked with bold font style and differences between 10°-20° with italic font style. The averaged T_2 values within the ROI of the *M. tibialis* remain constant, whereas we found significant increase in the *M. soleus* (between ankle position 0°-20° and 10°-20°) and in the *M. gastrocnemius medialis* (between 0°-10° and 0°-20°). Comparing the calculated DTI parameters for these ankle positions we also found significant changes for the ADC and θ values in the corresponding muscles (see Table 1).

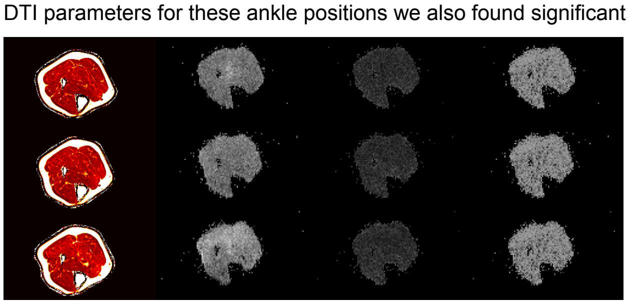

Fig. 2 *Parameter maps of T2, ADC, FA and θ (from left to right). In the M. soleus and M. gastrocnemius medialis an increase of T_2 and ADC is visible, whereas those parameters seem to remain constant in the M. tibialis.*

Table 1.	T2 [ms]		ADC [10^{-3} mm²/s]		FA [a.u.]		θ [°]	
	mean	SD	mean	SD	mean	SD	mean	SD
M. tibialis (0°)	53.41	7.85	1.14	0.20	0.54	0.16	70.24	14.86
M. tibialis (10°)	52.61	10.91	1.09	0.20	0.55	0.15	68.54	15.63
M. tibialis (20°)	52.83	7.97	**0.97**	0.23	0.59	0.15	68.17	17.14
M. soleus (0°)	60.25	11.73	1.29	0.18	0.47	0.11	72.85	12.75
M. soleus (10°)	61.35	13.45	1.23	0.20	0.45	0.12	74.14	12.93
M. soleus (20°)	***67.79***	13.26	***1.59***	0.23	**0.43**	0.10	***60.30***	19.55
M. g. medialis (0°)	55.62	9.05	1.22	0.18	0.50	0.14	73.71	10.26
M. g. medialis (10°)	**61.47**	14.96	**1.31**	0.20	**0.44**	0.14	**69.12**	18.11
M. g. medialis (20°)	**61.31**	17.28	***1.48***	0.23	**0.43**	0.14	**68.98**	15.33

Discussion This study demonstrates the feasibility of *in vivo* DTI examinations of muscle tissue in voluntarily contracted calf muscles by using a MR compatible ergometer in combination with a clinical 3 T MR system and a STEAM based pulse sequence. Significant changes of DTI parameters were observed, e.g., reduction of the tensor angle within shortened muscles due to active contraction as expected. Hence, this framework opens a window to analyse 3D muscle architecture and deformation *in vivo*, thereby providing a deeper insight into contraction dynamics.

References

1. Sinha S and Sinha U. J Magn Reson Imaging. 2011; 34(1):107-19.
2. Schwenzer NF *et al*. NMR Biomed. 2009; 22(10):1047-53.
3. Deux JF *et al*. Eur. Radiol. 2008; 18(10):2303–10.
4. Okamoto Y *et al*. Magn Reson Med Sci. 2010; 9(1):1-8.
5. Hiepe P *et al*. Proceedings of ESMRMB, Leipzig, 2011.
6. Hiepe P *et al*. Proceedings of ISMRM, Stockholm, 2010.
7. Wang R and Wedeen VJ. Diffusion Toolkit, trackvis.org, 2009.