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Comparison of measurements of medial gastrocnemius architectural parameters from ultrasound and diffusion tensor images

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ABSTRACT

In vivo measurements of muscle architecture provide insight into inter-individual differences in muscle function and could be used to personalise musculoskeletal models. When muscle architecture is measured from ultrasound images, as is frequently done, it is assumed that fascicles are oriented in the image plane and, for some measurements, that the image plane is perpendicular to the aponeurosis at the intersection of fascicle and aponeurosis. This study presents an *in vivo* validation of these assumptions by comparing ultrasound image plane orientation to three-dimensional reconstructions of muscle fascicles and aponeuroses obtained with diffusion tensor imaging (DTI) and high-resolution anatomical MRI scans. It was found that muscle fascicles were oriented on average at $5.5 \pm 4.1^{\circ}$ to the ultrasound image plane. On average, ultrasound yielded similar measurements of fascicle lengths to DTI (difference < 3 mm), suggesting that the measurements were unbiased. The absolute difference in length between any pair of measurements made with ultrasound and DTI was substantial (10 mm or 20% of the mean), indicating that the measurements were imprecise. Pennation angles measured with ultrasound were significantly smaller than those measured with DTI (mean difference 6°). This difference was apparent only at the superficial insertion of the muscle fascicles so it was probably due to pressure on the skin applied by the ultrasound probes. It is concluded that ultrasound measurements of deep pennation angles and fascicle lengths in the medial gastrocnemius are unbiased but have a low precision and that superficial pennation angles are underestimated by approximately 10°. The low precision limits the use of ultrasound to personalise fascicle length in musculoskeletal models.

1. Introduction

The capacity of a muscle to generate force depends on its architecture. Muscle architecture is typically described by parameters such as fascicle lengths, pennation angles and cross-sectional areas. These parameters provide insight into muscle function (Lieber, 2002) and are among the most important inputs to musculoskeletal models (for example Hoy et al., 1990). Such models can predict muscle and joint forces that are difficult to measure non-invasively, so they can contribute to knowledge of the function and dysfunction of the human movement system. Musculoskeletal model predictions are known to be sensitive to variations of musculotendon properties, especially to tendon slack length and (optimal) fibre length (Ackland et al., 2012; Scovil and Ronsky, 2006) but less so to pennation angle (Zajac, 1988). Personalised musculoskeletal models (as opposed to conventional models that are based on cadaveric data) become more feasible when muscle-tendon properties can be measured *in vivo*. Under certain conditions, personalised models produce more accurate predictions than conventional models (see for example de Oliveira and Menegaldo, 2010; Gerus et al., 2012, 2013).

There are several ways of measuring skeletal muscle architecture. Ultrasound is often used for *in vivo* measurements because it is non-invasive, relatively low-cost and easy to use. Also, because ultrasound has good temporal resolution it can be used to capture videos of contracting muscles (Cronin and Lichtwark, 2013; Narici, 1999). A disadvantage is that conventional ultrasound only provides a two-dimensional image with a limited field of view. MRI has a higher spatial resolution and image volume, and is three-dimensional, but it requires longer acquisition times (*i.e.*, it has poor temporal resolution).

When using ultrasound to measure fascicle length and pennation it is necessary to ensure the ends of the fascicles are in the image plane and (for measures of pennation angle) that the image

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plane is perpendicular to the aponeurosis at the intersection of fascicle and aponeurosis. It will not always be possible to satisfy both these conditions simultaneously. Most investigators either align the ultrasound transducer perpendicular to the body surface, or orientate the transducer to give the clearest ultrasound image, and assume this ensures fascicles lie in the image plane and the aponeuroses are locally perpendicular. However, little evidence exists to validate these assumptions (Kwah et al., 2013). Misalignment will result in errors in architectural measures (Bénard et al., 2009; Klimstra et al., 2007) which could jeopardise the accuracy of musculoskeletal model predictions.

Several studies have attempted to validate measurements of muscle architecture. Most have involved comparison with direct measurements made on cadavers (Ando et al., 2014; Bénard et al., 2009; Chleboun et al., 2001; Engelina et al., 2014; Kellis et al., 2009; for review see Kwah et al., 2013). The interpretation of these studies is uncertain because the course of an individual fascicle is difficult to follow in anatomical specimens, so the anatomical measurements may constitute a poor reference standard. Furthermore, cadaveric studies have analysed only a few locations in few muscles.

An alternative reference standard is diffusion tensor imaging (DTI). DTI uses MRI protocols that generate a signal that is dependent on the displacements of water molecules (Mori and Zhang, 2006). Skeletal muscle tissue has a structure which causes water molecules to move primarily along the long axis of fascicles. Identification of the primary direction of diffusion with DTI permits reconstruction of the course of muscle fascicles in three dimensions. There is evidence such reconstructions align well with true fascicles, at least in the rat gastrocnemius muscle (Damon et al., 2002). Recently, DTI has been used to study anatomical features of several human skeletal muscles, including the forearm muscles (Froeling et al., 2012), the tibialis anterior muscle (Lansdown et al., 2007) and the soleus muscle (Sinha et al., 2011).

Table 1
Characteristics of participants, expressed as mean ± SD.

Characteristic	Value
Age (years)	29.5 ± 5.7
Gender (M:F)	4:4
Height (cm)	164.4 ± 6.0
Weight (kg)	61.9 ± 11.8
Shank length (cm)	37.9 ± 1.88

The aim of this study was to compare ultrasound measures of fascicle length and pennation angle to the same measures obtained with DTI. To do so we developed a new DTI-based method for measuring fascicle length and pennation and applied these methods to the human medial gastrocnemius muscle.

2. Methods

A group of eight healthy subjects without known lower limb musculoskeletal pathology participated in the study (Table 1). Fascicle orientations, fascicle lengths and pennation angles were obtained at 16 locations in the left medial gastrocnemius by two methods, one based on ultrasound and the other based on DTI and MRI data. The estimates were then compared. All measurements were conducted under static, passive conditions with the subjects lying supine. The procedures conformed to the Declaration of Helsinki and were approved by the local research ethics committee. Informed consent of all subjects was obtained prior to their participation.

2.1. DTI fascicle reconstruction

The subject's ankle was strapped into an MRI-compatible splint that fixed the left foot at an angle of 80° with respect to the horizontal plane, while the left knee was kept in a slight flexion angle (Fig. 1). On average the ankle was dorsiflexed 7° (SD 2°), where 0° indicates that the anterior tibial border was perpendicular to the sole of the foot. A wedge was placed under the thigh so that the calf did not make contact with the MRI table and thus was not deformed by compression from the weight of the leg. The knee angle was measured with an MRI-compatible inclinometer just before scanning so that the same knee orientation could be reproduced for the ultrasound measurements that were performed afterwards.

From each subject, 75 axial MRI and DTI images of the left lower leg from the ankle to the knee were obtained with a 3T MRI scanner (Achieva 1.2, Philips Medical Systems, Best, The Netherlands). The T1-weighted anatomical scan was obtained with the following settings: TSE sequence, TR/TE 1842/8 ms, field of view (FOV) 180 mm, acquisition matrix 288 × 215 (reconstructed to 960 × 960), voxel size 0.1875 × 0.1875 × 5 mm, scan time 320 s. The settings for the DTI scans were: EPI sequence, TR/TE 8522/63 ms, FOV 180 mm, voxel size 1.875 × 1.875 × 5 mm, 16 gradient directions on a hemisphere, number of signal averages 2, $b = 500$ s/mm^2 (B0 image with $b = 0$ s/mm^2), scan time 298 s. The DTI scan was repeated with the same settings. The anatomical scan had a higher resolution than the DTI scans but all scans were made in the same coordinate system. Transformation matrices from voxel indices to this coordinate system were provided by the scanner.

The boundary of the medial gastrocnemius was manually outlined on each of the MRI slices and a 3-D triangulated surface model of the muscle was generated (Amira 5.5.0, FEI Corp., Hillsboro, USA). The surface model was remeshed to 10,000 triangles (resulting in edge lengths of approximately 1.8 mm) and smoothed (ReMESH 2.1alpha, Uniform Remesh to 10,000 vertices, Laplacian Smooth, 1 iteration).

Electronic supplement 1 in Appendix provides a full description of how fascicles were reconstructed from the DTI and anatomical MRI scans. Briefly, DTI data were denoised (Manjon et al., 2013) and DSI studio (October 2013 build) was used to calculate the fractional anisotropy (FA) and primary diffusion directions for each voxel and to perform fibre tractography (Yeh et al., 2013). Tractography was used to generate 100 tracts through a small region around each of the ultrasound-

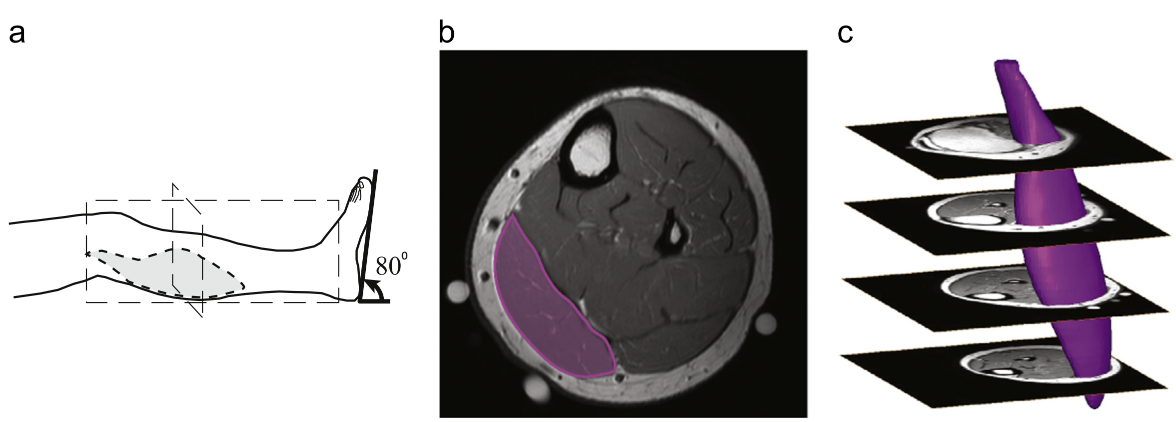

Fig. 1. (a) The field of view of MRI and DTI scan (indicated by the dashed lines) extended from the ankle to the knee of the subject's left lower leg. (b) Example of a T1-weighted axial slice. The pink shaded area is the medial gastrocnemius. MRI markers used for aligning MRI and ultrasound coordinate systems appear as white circles on the surface of the leg. (c) A three-dimensional triangulated surface model of the medial gastrocnemius created from the masked volume. Only 4 of the 75 axial slices are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)