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Ultrasound imaging of the human medial gastrocnemius muscle: how to orient the transducer so that muscle fascicles lie in the image plane

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ABSTRACT

The length and pennation of muscle fascicles are frequently measured using ultrasonography. Conventional ultrasonography imaging methods only provide two-dimensional images of muscles, but muscles have complex three-dimensional arrangements. The most accurate measurements will be obtained when the ultrasound transducer is oriented so that endpoints of a fascicle lie on the ultrasound image plane and the image plane is oriented perpendicular to the aponeurosis, but little is known about how to find this optimal transducer orientation in the frequently-studied medial gastrocnemius muscle. In the current study, we determined the optimal transducer orientation at 9 sites in the medial gastrocnemius muscle of 8 human subjects by calculating the angle of misalignment between three-dimensional muscle fascicles, reconstructed from diffusion tensor images, and the plane of a virtual ultrasound image. The misalignment angle was calculated for a range of tilts and rotations of the ultrasound transducer relative to a reference orientation that was perpendicular to the skin and parallel to the tibia. With the transducer in the reference orientation, the misalignment was substantial (mean across sites and subjects of 6.5°, range 1.4 to 20.2°). However for all sites and subjects a near-optimal alignment (on average 2.6°, range 0.5° to 6.0°) could be achieved by maintaining 0° tilt and applying a small rotation (typically less than 10°). On the basis of these data we recommend that ultrasonographic measurements of medial gastrocnemius muscle fascicle architecture be obtained, at least for relaxed muscles under static conditions, with the transducer oriented perpendicular to the skin and nearly parallel to the tibia.

1. Introduction

The length and orientation of the fascicles in a muscle determine the muscle's force-generating capacity. Fascicle lengths and orientations (pennation angles) have therefore been measured to obtain insight into normal muscle function (for example Darby et al., 2013; Fukunaga et al., 1997; Herbert et al., 2015) as well as muscle function in children with cerebral palsy (Shortland et al., 2002) or adults with stroke (Gao et al., 2009) or spinal cord injury (Diong et al., 2012). Measurements of muscle architecture are also required for realistic predictions of muscle and joint function with biomechanical models (Ackland et al., 2012; Anderson and Pandy, 2001; Gerus et al., 2015). The architecture of the human medial gastrocnemius muscle is commonly studied because of its importance in locomotion.

The most widely used method for obtaining non-invasive measurements of muscle fascicle length and pennation (muscle architecture) from humans in vivo is ultrasound imaging. The main benefits of ultrasound are its ease of application, relatively low cost and excellent temporal resolution compared to other non-invasive methods such as magnetic resonance imaging (MRI). Measurements of muscle architecture obtained with ultrasonography are generally reliable but their validity is not well established (Kwah et al., 2013).

An important potential source of error in ultrasound imaging-based measurements of muscle architecture is the alignment of the ultrasound transducer (Bénard et al., 2009; Klimstra et al., 2007). The transducer alignment determines which part of the three-dimensional muscle volume is visible on the two-dimensional ultrasound image. Theoretically, for measurement of muscle fascicle length, optimal alignment is achieved when both ends of the measured fascicle lie in the plane of the ultrasound image. For measurement of pennation angles, optimal alignment is achieved when, in addition, the image plane is locally perpendicular to the aponeurosis (i.e. intersects the aponeurosis at a 90° angle). Despite the widespread use of ultrasound to measure muscle architecture, the best strategy to satisfy these criteria is not yet known. Bénard et al. (2009) noted that one of two strategies is typically adopted: either the transducer is oriented perpendicular to the skin or the transducer is oriented to obtain a clear image of

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the striated pattern of muscle fascicles. By comparing ultrasound-based measures of muscle fascicle length with measurements obtained directly from four cadaveric gastrocnemius muscles, they found that orienting the transducer perpendicular to the skin can lead to substantial errors in architecture measurements. (The medial gastrocnemius is one of the most commonly studied muscles and it is the muscle that we study here.) The alternative approach relies on the assumption that clear images arise when the muscle fascicles lie in the image plane. This approach requires the operator to make a subjective judgement on image quality, and might therefore be less reproducible.

We recently developed a method that uses MRI and diffusion tensor imaging (DTI, an emerging MRI technique to reconstruct muscle fascicle architecture in vivo) to reconstruct fascicles three-dimensionally at any point in the medial gastrocnemius muscle (Bolsterlee et al., 2015). Using these methods, we found that fascicles on clear ultrasound images make an angle of, on average, 5.5° to the image plane. The mean, absolute errors in length and pennation angle measurements of these fascicles were 10 mm and 6°, respectively. In the current study we used MRI and DTI to determine how the ultrasound transducer should be oriented to align the ultrasound image plane with muscle fascicles in the human medial gastrocnemius.

2. Methods

For the present study we conducted a further analysis of MRI and DTI data that had been collected for a previous study (Bolsterlee et al., 2015). Participants were 4 men and 4 women, all healthy, aged 29.5 ± 5.7 years, height 164.4 ± 6.0 cm, weight 61.9 ± 11.8 kg, shank length 37.9 ± 1.9 cm. (These and other data are means ± SD.) T1-weighted anatomical scans and DTI scans were conducted with the left ankle positioned in slight dorsiflexion ($7° \pm 2°$, where 0° means the sole of the foot was perpendicular to the tibia). For the original analysis we created three-dimensional surface models of the leg and the medial gastrocnemius muscle. A method based on DTI fibre tracking was developed to reconstruct the location of the two endpoints of muscle fascicles. The methods used to acquire MRI and DTI data and reconstruct muscle fascicles have been described in detail elsewhere (Bolsterlee et al., 2015).

2.1. DTI fascicle reconstruction

The goal of DTI fibre tracking was to find the endpoints of many muscle fascicles in the medial gastrocnemius. We will refer to a line that connects two endpoints as a ‘fascicle’ even though we recognise that the linear paths of the fascicles in this study differ from the potentially curved paths of real muscle fascicles. We chose to use a linear approximation to fascicle paths because the requirement for accurate measurement of muscle architecture with ultrasound is that both endpoints of the fascicle lie in the image plane - it is thus not necessary to determine the true curvilinear course of muscle fascicles to identify the optimal orientation of the ultrasound plane, as we further explain in Section 2.2.

Whereas in our previous study only 16 fascicles per subject were reconstructed, we now applied the same algorithms to reconstruct >700 fascicles per subject (Table 1). Fascicles were seeded (i.e., tracts were initiated) at many sites in the muscle. For each slice in which the muscle was visible, seed sites were selected from each posterior-anterior row of voxels that contained the deep and superficial aponeurosis. The seed site consisted of a 9-voxel region that contained the voxel midway between the superficial and deep aponeuroses and its 8 neighbours in the axial plane (Fig. 1a). A deterministic fibre tracking algorithm (Yeh et al., 2013) was started from each seed region (settings: $0.1 < \text{fractional anisotropy} < 0.7$, $20\ \text{mm} \leq \text{tract length} \leq 200$ mm, max. angle = 10°, stepsize 1 mm) to find 100 tracts that intersected both the superficial and deep aponeuroses (represented as 1-voxel thick surfaces). If, at any seed site, no tracts were found that satisfied these constraints, the requirement of intersecting both the superficial aponeurosis and deep aponeurosis was relaxed and fibre tracking was repeated. To reconstruct the two corresponding fascicle endpoints from the fibre tracts, the tracts were first trimmed whenever they intersected the muscle surface, then the centroid of the 100 tract endpoints at either end of the bundle was calculated, and finally the line connecting the two endpoints was extended until both endpoints were positioned on the muscle surface (Bolsterlee et al., 2015). All fascicles of all subjects were visually checked and given a rating for plausibility. Implausible tracts (for example, tracts that ran parallel to the aponeuroses for large distances) were excluded from further analyses (Table 1). We used DSI Studio (October 2013 build) for fibre tracking and Matlab R2013b (The MathWorks, Inc., Natick, Massachusetts, United States) for all other analyses. Fig. 2

2.2. Misalignment calculation

The ultrasound transducer is oriented optimally for the measurement of the length of a particular muscle fascicle when both endpoints of the fascicle lie in the plane of the two-dimensional ultrasound image. The line connecting the two endpoints (the ‘fascicle’) is then parallel to the ultrasound image plane, i.e. it makes an angle of 0° to that plane. The angle between a fascicle and ultrasound image plane (φ) thus serves as a measure of how well the ultrasound transducer is oriented for measurement of the length of that fascicle. Many fascicles are visible in any one ultrasound image, so the mean φ of all fascicles in the ultrasound image can provide a measure of transducer misalignment. Using the DTI-based fascicle reconstructions, the mean misalignment

Table 1
Success and plausibility rates of DTI tractography per subject.

Subject	Number of seeds	No tracts found (%) [a]	Implausible (%)	Plausible (%)	Number of fascicles
1	1142	9.4	27.1	63.5	725
2	1010	5.6	22.1	72.3	730
3	1058	7.6	32.3	60.1	636
4	1042	13.9	28.2	57.9	603
5	1342	14.2	23.4	62.4	837
6	1052	7.2	24.5	68.3	718
7	1444	12.6	17.4	70.0	1011
8	1034	12.9	29.1	58.0	600
Mean ± SD	1140.5 ± 152.2	10.4 ± 3.2	25.5 ± 4.4	64.1 ± 5.2	732.5 ± 137.5

[a] ‘No tracts found’ means that the tractography algorithm could not find 100 tracts that satisfied the constraints and passed through the seed region.