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Computational methods for quantifying *in vivo* muscle fascicle curvature from ultrasound images

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ABSTRACT

Muscle fascicles curve during contraction, and this has been seen using B-mode ultrasound. Curvature can vary along a fascicle, and amongst the fascicles within a muscle. The purpose of this study was to develop an automated method for quantifying curvature across the entirety of an imaged muscle, to test the accuracy of the method against synthetic images of known curvature and noise, and to test the sensitivity of the method to ultrasound probe placement. Both synthetic and ultrasound images were processed using multiscale vessel enhancement filtering to accentuate the muscle fascicles, wavelet-based methods were used to quantify fascicle orientations and curvature distribution grids were produced by quantifying local curvatures for each point within the image. Ultrasound images of ramped isometric contractions of the human medial gastrocnemius were acquired in a test–retest study.

The methods enabled distinct curvatures to be determined in different regions of the muscle. The methods were sensitive to kernel sizes during image processing, noise within the image and the variability of probe placements during retesting. Across the physiological range of curvatures and noise, curvatures calculated from validation grids were quantified with a typical standard error of less than 0.026 m^{-1}, and this is about 1% of the maximum curvatures observed in fascicles of contracting muscle.

1. Introduction

Muscle fascicles must be curved in order to maintain mechanical equilibrium within pennate muscle (van Leeuwen and Spoor, 1996). During contraction the curvature of the muscle fascicles increases (Hill, 1948; Kawakami et al., 2000; Blazevich et al., 2006; Otten, 1988; van Leeuwen and Spoor, 1992; Maganaris et al., 1998) and these increases have been linked to the internal forces and pressures within the muscle (van Leeuwen and Spoor, 1992). When a muscle fascicle curves, its trajectory changes along its length and displays a longer length than the commonly assumed linear approximation that shares the same origin and insertion (Muramatsu et al., 2002); thus, it is important to quantify fascicle curvature in order to understand details of fascicle strain and pennation angle (Kawakami et al., 1998; Styf et al., 1995).

To date, only a few studies have predicted (van Leeuwen and Spoor, 1992; Sejersted et al., 1984) or quantified curvatures of the muscle fascicles (Kawakami et al., 1998; Muramatsu et al., 2002; Stark and Schilling, 2010; Wang et al., 2009). Previous ultrasound-based studies have used manual digitisation to quantify the path of select fascicles in ultrasound images of muscle. However this process is both time-consuming and can be subjective. Recent developments in the processing of ultrasound images allow the local orientations of all fascicles within a muscle image to be determined (Rana et al., 2009), and these orientation grids provide the information necessary to calculate local curvatures at all points across a muscle image.

The purpose of this study was to (1) develop automated techniques to quantify local fascicle curvatures from the orientation grids of fascicles within a muscle; (2) validate these methods against synthetic test images containing known curvature and noise; and (3) determine the sensitivity of these automated curvature quantification methods to ultrasound placement and contraction level for the medial gastrocnemius muscle.

2. Methods

B-mode ultrasound images were collected (Fig. 1) using a 2D linear ultrasound probe (Echoblaster 128 EXT-1Z, Telemed, Lithuania) at an 8 MHz wave frequency and the images were collected from the medial gastrocnemius of a healthy male subject at a frame rate of 50 Hz. Images of the muscle were 384 pixels wide and extended approximately 150 pixels into the muscle. The subject was seated in a dynamometer (System 3, Biodex, New York, USA) with the right ankle fixed at 75° relative to the tibia. The subject was instructed to perform an isometric contraction

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