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In-vivo determination of 3D muscle architecture of human muscle using free hand ultrasound

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ABSTRACT

Muscle architecture is an important parameter affecting the muscle function. Most of the previous studies on *in-vivo* muscle architecture have used in 2D ultrasound. The importance of the third dimension has not been much explored due to lack of appropriate methods. DT-MRI has been used to study muscle architecture in 3D, however, due to long scan times of about 15 min DT-MRI has not been suitable to study active muscle contractions. The purpose of this study was to develop and validate methods to determine *in-vivo* muscle fascicle orientations in 3D using ultrasound. We have used 2D ultrasound and a 3D position tracker system to find the 3D fascicle orientation in 3D space. 2D orientations were obtained by using automated methods developed in our previous studies and we have extended these in the current study to obtain the 3D muscle fascicle orientation in 3D space. The methods were validated using the physical phantom and we found that the mean error in the measurement was less than 0.5° in each of the three co-ordinate planes. These methods can be achieved with short scan times (less than 2 min for the gastrocnemii) and will thus enable future studies to quantify 3D muscle architecture during sub-maximal voluntary contractions.

1. Introduction

Muscle architecture is a major determinant of the mechanical function of skeletal muscle. Muscle fascicle orientation is an important architectural parameter affecting the muscle properties. Previous studies in different species have shown regionalization of fascicle architecture in muscle and these differences in architecture have been related to differential activation patterns and function of muscles (Blazevich et al., 2006; Herring et al., 1979; Wakeling, 2009).

From the last two decades, brightness mode (B-mode) ultrasonography has been used to study muscle architecture in two dimensions (Kawakami et al., 1993; Kuno and Fukunaga, 1995). Muscle fascicle architecture can be quantified non-invasively using diagnostic ultrasound for both dynamic and isometric contractions (Fukunaga et al., 1997a; Fukunaga et al., 1997b; Ito et al., 1998; Kawakami et al., 1998; Maganaris et al., 1998). Ultrasound probes are typically less than 60 mm and so B-mode ultrasound scans do not image the whole muscle. Additionally, each scan represents a 2D slice through the muscle, and hence information in the third dimension is lost. Because of this, studies using 2D ultrasound usually image the muscle belly and implicitly assume that the 2D information from the belly is representative of the whole muscle. 3D trajectories of the muscle fascicles must be quantified in order to test the assumption that the whole muscle properties can be explained from the 2D ultrasound images of muscle belly. In order to do so, we need to develop reliable and validated methods to quantify the 3D muscle architecture across the whole muscle. Muscle fascicle structure is visible in ultrasound images for a range of probe orientations; however, the optimal alignment of the probe for 2D studies is for the muscle fascicles to lie within the scanning plane. An error of up to 23% has been reported in fascicle angles for probe orientations that do not align the fascicles with the scanning plane (Benard et al., 2009). Thus, it is also important to develop robust methods that are not sensitive to the probe orientation. Studying the muscle fascicle architecture in 3D will help to alleviate this problem.

Diffusion tensor magnetic resonance imaging (DT-MRI) has previously been used for muscle fiber tracking. The reported scan times in recent studies are at least 15 min (Budzik et al., 2007; Heemskerk et al., 2009), but active muscle contractions cannot be sustained for these durations. Also, DT-MRI is very sensitive to soft tissue motion that may occur due to prolonged contractions (Bishop et al., 2009). One notably fast DT-MRI study (2.5 min; Deux et al., 2008) reported that the diffusion co-efficient may not relate to the direction of the fascicles due to a loss of diffusion anisotropy with these rapid scans. To date, DT-MRI studies have been used mostly to study architecture in passive muscle. On the other hand, ultrasound is cheaper, and makes real-time acquisition

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