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Assessment of intramuscular activation patterns using ultrasound M-mode strain

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ABSTRACT

The intramuscular activation pattern can be connected to the motor unit recruitment strategy of force generation and fatigue resistance. Electromyography has earlier been used in several studies to quantify the spatial inhomogeneity of the muscle activation. We applied ultrasound M-mode strain to study the activation pattern through the tissue deformation. Correlation values of the strain at different force levels were used to quantify the spatial changes in the activation. The assessment was done including the biceps brachii muscle of 8 healthy subjects performing isometric elbow flexion contractions ranging from 0% to 80% of maximum voluntary contraction. The obtained results were repeatable and demonstrated consistent changes of the correlation values during force regulation, in agreement with previously presented EMG-results. Both intra-subject and inter-subject activation patterns of strain were considered along and transverse the fiber direction. The results suggest that ultrasound M-mode strain can be used as a complementary method to study intramuscular activation patterns with high spatial resolution.

1. Introduction

The muscular force generation is regulated by recruitment of individual motor units and by varying the firing rate (De Luca et al., 1982; Milner-Brown et al., 1973). The spatial distribution of motor unit recruitment is not uniform, but different parts of the muscle are dominantly active depending on force level and can also vary over time with sustained contraction (English and Weeks, 1984; Grassme et al., 2003; Holtermann and Roeleveld, 2006). This is partly dependent on how different fiber types are distributed but also, as presented by Henneman in 1965, dependent on the size of the motor units; where larger, faster and less fatigue resistant motor units are recruited as the force production increases (Henneman et al., 1965). The spatial inhomogeneity has been shown in several studies using multi-channel surface electromyography (MCSEMG) on biceps brachii and the trapezius muscle during force regulation and fatigue (Farina et al., 2008; Holtermann and Roeleveld, 2006; Holtermann et al., 2005; Madeleine et al., 2006). In addition, the muscular recruitment strategy is connected to fatigue prevention and has been demonstrated to be related to pain intensity (Holtermann et al., 2010, 2011). Therefore, the spatial variation of the neuromuscular control is of great interest when it comes to neuromuscular disorders, muscle weakness and work related muscle pain conditions (Gerdle et al., 2010; Madeleine et al., 2006).

The contraction of the muscle is initiated from the depolarization of the cell membrane giving rise to an electrical action potential propagating along the fiber. The contractile properties of the muscle fibers lead to either thickening or thinning of the tissue while also shortening or lengthening during a contraction, in accordance to the neuro-motor generated innervations. Muscular function and recruitment strategies have so far mainly been investigated by the use of electromyography (EMG) which is the most common technique to map activity patterns of the muscles. This provides information about the neurological input, fiber characteristics and force development in the muscle (Basmajian and DeLuca, 1985). However, in general, the EMG offers poor spatial resolution and difficulties reaching deep musculature without using invasive needles.

Imaging techniques such as magnetic resonance imaging (MRI) and ultrasound have primarily been used to study the size and architectural parameters of muscles (Fukunaga et al., 1997; Kawakami et al., 2006; Narici, 1999). Due to the high temporal resolution ultrasound is also suitable for studying functional movements in real time and reducing the limitation of only measuring on a local area of the muscle. In cardiological applications post-process techniques has been used the last decades to analyze and quantify motion and deformation parameters, such as speckle tracking and tissue Doppler (D'Hooge et al., 2002, 2000; Stoylen, 2001; Sutherland et al., 2004). Recently several studies have reported the application of ultrasound based methods to quantify

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the mechanics of skeletal muscle tissue (Lindberg et al., 2011; Peolsson et al., 2012, 2010; Pulkovski et al., 2008; Shi et al., 2007).

Tissue activity can be described through the tissue deformation and the parameter strain, expressed as the percentage of shortening or lengthening compared to rest (i.e. compression or elongation). Regional strain comes to express different aspects of tissue dynamics, such as contractility, coordination- and activity patterns (Peolsson et al., 2008; Stoylen, 2001). Depending on how the muscle is located it may be easier to analyze the strain either along or transverse the fiber direction. For example imaging trapezius, which is a flat, triangular muscle, the number of possible projections is limited. The aim of this study was to assess the feasibility to quantify the intra-muscular activation patterns using ultrasound motion mode (M-mode) strain imaging. An additional aim was to study differences in the strain pattern along and transverse to the direction of the muscle fiber.

2. Materials and methods

2.1. Subjects

Eight healthy male subjects participated in the study (age: 25 ± 4 years; height: 180 ± 17 cm; weight: 84 ± 26 kg; right arm circumference: 26 ± 6 cm). None of the subjects had experienced any pain or injury of the upper extremities and the right arm was dominant for all subjects. Each participant gave a written consent prior to the study, which also was conformed to the declaration of Helsinki and approved by the local ethics committee.

2.2. Experimental setup and data collection

The subjects were positioned in an upright position in a dynamometer equipped chair (Kin-Com 500H, Chattanooga Group, Inc., Tennessee, USA) with their right arm attached to the lever arm foundation of the dynamometer. Before the measurements the subjects performed three isometric maximum voluntary contractions (MVCs) with 1 min recovery between each contraction to determine the maximal exerted force. The largest recorded force was used for normalization. Each subject performed two separate sets of one isometric elbow flexion contraction, ranging from 0% up to 80% MVC and back to 0% MVC. The total contraction time was 10 s, with 5 s each of ascending and descending force. The elbow joint was angled at approximately 135°. A 3 min rest was included between the sets and a replacement of the ultrasound probe was made between the ultrasound recordings of the different sets. The flexion torque was measured with the dynamometer and real time visual feedback of the torque values were displayed on a computer screen located in front of the subjects presenting a curve with the target force (including interval with +/−5% MVC) and the produced force.

Longitudinal images of biceps brachii were recorded with an ultrasound scanner (Vivid7, GE Vingmed, Horton, Norway) using a 12 MHz linear transducer. The ultrasound probe was held fixed by a custom-made arm and placed on the medial side of the upper arm. In addition, the probe was centered on the muscle belly with its cross section in the axial direction of the arm. The acquisition depth and width were set to 4.5 cm and 3 cm, respectively with a frame rate of 49 Hz. One focus point at a depth of 2.5 cm was set in the middle of the biceps brachii to focus the ultrasonic beam. The ultrasonic scanner was set to use no compounding, and no spatial or temporal filtering of the acquired data. The resolution of the B-mode images was 584 × 251 pixels, corresponding to a spatial resolution of 0.0077 × 0.0118 cm/pixel. B-mode image sequence data was converted to hdf5 data format using the software EchoPac (version BT-08, GE VingMed, Horten, Norway) and then further analyzed in MATLAB (2011b, Mathworks, Nattick, MA, USA).

2.3. Estimation of tissue M-mode strain

M-mode strain was used to access the intramuscular activity pattern over time. The different calculation steps are described below and illustrated in Fig. 1.

Tissue velocities were estimated from the B-mode image sequence using a speckle tracking technique. The speckle tracking was performed on consecutive B-mode image frames using the method described by Lin et al. (Lin et al., 2007). This method estimates the velocity vectors in a grid pattern using a hierarchical block-matching scheme (coarse to fine level) using the mean squared error cost function and an adaptive spatial vector filter based on local image features. Three levels were used in the hierarchical block-matching scheme in this study. The matching block size was set to 0.85 × 2.54 mm^2 (axial × lateral) within a search region of 0.69 × 2.07 mm (axial × lateral), and this gives an upper limit to the estimated axial and lateral tissue velocity of 3.45 cm/s and 10.35 cm/s, respectively, and a spatial resolution of 0.0306 × 0.0461 cm/pixel.

Strain rate was estimated through the spatial gradient of the tissue velocity and strain by integrating the strain rate over time. The spatial resolution of strain is affected by the number of velocity values included in the estimation of the spatial gradients. Here

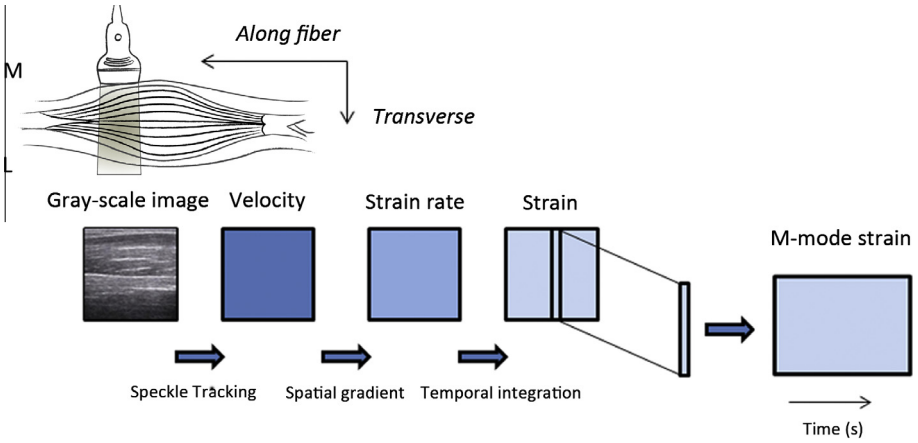

Fig. 1. Block scheme illustrating how the M-mode strain is calculated from the ultrasound images. Speckle tracking of the grayscale images results in 2-dimensional velocities and according to the presented scheme strain rate, strain and M-mode strain can be calculated both along and transverse to the fiber direction. "M" and "L" mark the medial and lateral parts of biceps brachii.