Ultrasound in Med. & Biol., Vol. 37, No. 7, pp. 1151–1160, 2011

0301-5629/$ - see front matter

doi:10.1016/j.ultrasmedbio.2011.04.006

● *Original Contribution*

PENNATION ANGLE DEPENDENCY IN SKELETAL MUSCLE TISSUE DOPPLER STRAIN IN DYNAMIC CONTRACTIONS

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(*Received* 11 *November* 2010; *revised* 28 *March* 2011; *in final form* 17 *April* 2011)

Abstract—Tissue velocity imaging (TVI) is a Doppler based ultrasound technique that can be used to study regional deformation in skeletal muscle tissue. The aim of this study was to develop a biomechanical model to describe the TVI strain's dependency on the pennation angle. We demonstrate its impact as the subsequent strain measurement error using dynamic elbow contractions from the medial and the lateral part of biceps brachii at two different loadings; 5% and 25% of maximum voluntary contraction (MVC). The estimated pennation angles were on average about 4° in extended position and increased to a maximal of 13° in flexed elbow position. The corresponding relative angular error spread from around 7% up to around 40%. To accurately apply TVI on skeletal muscles, the error due to angle changes should be compensated for. As a suggestion, this could be done according to the presented model. (E-mail: frida.lindberg@sth.kth.se) © 2011 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Ultrasound, Tissue Doppler, Skeletal muscle, Pennation angle, Strain, Biceps brachii.**

INTRODUCTION

Today there are a number of techniques that describe the dynamics of skeletal muscles. Electromyography (EMG) is the most commonly used technique to map activity patterns of the muscles providing information about the neurologic input, fiber characteristics and force development in the muscle (Basmajian and DeLuca 1985). However, EMG offers a poor spatial resolution and it does not in general provide any information about muscle structure and mechanical aspects. Imaging techniques such as magnetic resonance imaging (MRI) and ultrasound imaging have mainly been used to study the size and architectural parameters of muscles since they have a great impact on the muscle force production and high spatial resolution (Herbert and Gandevia 1995; Fukunaga et al. 1997; Narici 1999; Blazevich et al. 2006; Kawakami et al. 2006). The high temporal resolution makes ultrasound specially suited as a technique when it comes to studying structural movements in real-time (Shi et al. 2008). Also, the low cost, availability and ease of examination makes ultrasound superior to MRI in applications of skeletal muscle dynamics. The image resolution in ultrasound equipments has increased rapidly and advanced post-process commercial and semicommercial software packages are available.

Tissue velocity imaging

Tissue velocity imaging (TVI) is a technique used for quantitative analysis of ultrasound image sequences and based on the Doppler principle (D'Hooge et al. 2000; Urheim et al. 2000; Stoylen 2001; Sutherland et al. 2004). Traditionally, the Doppler technique has been used to calculate velocities in blood. In this case, high Doppler frequencies correspond to blood velocities and lower frequencies are consequently filtered out. However, lower frequencies of the signal carry information about the tissue surrounding the blood volume. Technically, a low pass filter can be implemented to bring forward the frequencies of the signal that correspond to the tissue velocities. In commercially available clinical scanners, auto

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correlation of the phase shift is often used as estimation methodology of tissue velocity and tissue deformation (D'hooge 2006).

TVI was initially developed for cardiologic applications and has for the last 10 years been used clinically. The technique provides visual information on overall anatomy, movement and velocities of the cardiac muscle tissue together with quantitative measurements of these parameters. As a result, integrated information of a patient's heart both on a local and global scale is acquired (see Brodin 2004; Storaa et al. 2004; Sutherland et al. 2004 for an overview). The method has been validated according to regional myocardial velocities (Urheim et al. 2000) and inter- and intrasubject reproducibility have been found in the range of 5%–10% (Gaballa et al. 2001; Frazier 2003).

There are a number of studies on the angular dependency of Doppler based ultrasound in echocardiographic strain imaging. In clinical practice, this is not considered to have an important influence on either timing on specific events or on the profiles of the curves (Heimdal 1999; D'Hooge et al. 2000; Storaa et al. 2003). In case of a myocardial imaging, this problem is partially considered to be avoided by making sure that the insonation is either perpendicular or parallel to the myocardial wall. Also, by making some simple assumptions about how the heart deforms, compensation is possible (Heimdal 1999; D'Hooge et al. 2000).

TVI has been used in a pilot study according to skeletal muscle using a global velocity parameter (Grubb et al. 1995). Other recent studies have also presented TVI as a method applied on skeletal muscles (Mannion et al. 2008; Peolsson et al. 2008). However, the angular dependency in such recordings has not been explored.

Tissue mechanical parameters

Because of the elasticity of muscle tissue, it will undergo dynamic changes due to neuro-motor generated innervations. In TVI two concepts can be used to describe tissue activity: movement and deformation. To describe tissue movement, the variables *velocity* and *displacement* are used. Velocity is a variable that describes tissue velocities in the direction toward and away from the ultrasound probe. Displacement describes the distance that the muscle tissue moves in the same directions. The velocity information is generated by estimating the phase shift using the auto correlation method. In its turn, displacement is calculated by integrated velocities (Brodin 2004; D'hooge 2006).

In the case of tissue deformation, the variables *strain* and *strain rate* are used (Dickinson and Hill 1982; Robinson et al. 1982; Wilson and Robinson 1982). The concept of strain was initially presented by Mirsky and Parmley (1973) to describe elasticity and stiffness in heart muscle. Strain is the degree of tissue deformation expressed as the percentage of shortening or lengthening compared with rest (*i.e.*, compression or elongation). Strain rate on the other hand is the rate at which this deformation occurs and calculated as the spatial gradient of the velocity. When applying these four modalities in the analysis of functional movements, they come to express different aspects of tissue dynamic, such as contractility, coordination and activity patterns (Peolsson et al. 2008). Inflammatory conditions and functional disorders are examples of which the tissue deformation can be of interest. However, the clinical value has to be verified in further studies.

Muscle tissue is assumed to be nearly incompressible, disregarding the blood volume that will be squeezed out of the muscle during a contraction. The incompressibility means that the volume of the muscle remains constant during compression. Furthermore, due to the volume conservation, strain in one direction has to be compensated by inverse strain in other directions. Therefore, under the assumption of no shear strain, the sum of strain in all directions must be zero (Stoylen 2001). Thus, strain measured in the axial direction can be seen as thickening or thinning of the muscle. The result is usually presented using color coding superimposed on the gray-scale images (see D'Hooge et al. 2000; Stoylen 2001; Weidemann et al. 2001; D'Hooge et al. 2002 for more details).

Cylindrical model

In general, most soft tissues are anisotropic, viscoelastic and nonlinear. However, the mechanical properties are often modeled to behave as linear, elastic, isotropic materials to simplify analysis (Krouskop et al. 1998; Ophir et al. 1999). A skeletal muscle can be modeled as a cylinder with poroelastic properties. During a contraction phase, the muscle fiber is subjected to a negative longitudinal strain (*i.e.*, shortening) and a positive axial strain (*i.e.*, thickening). Treating the tissue as a linearly elastic, isotropic material, Poisson's ratio (ν) is a material constant that can be used to characterize the deformation in such material. This is the constant that describes the relation between axial and longitudinal strain. Earlier findings in animal (*e.g.*, Rapoport 1973) and human studies (*e.g.*, Ophir et al. 1999; Konofagou et al. 2001; Righetti et al. 2004) have shown that the Poisson's ratio of soft tissue is close to 0.5.

Muscle architecture

The spatial arrangement of the muscle fibers will have an important role when applying TVI. Fibers that run parallel along the central line of the muscle are parallel-fibered muscles. In this case, the Doppler signal accurately describes the axial strain of the muscle fibers