31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Measurement of Rectus Femoris Muscle Velocities During Patellar Tendon Jerk Using Vector Tissue Doppler Imaging

Siddhartha Sikdar, *Member, IEEE*, Maria Lebiedowska, Avinash Eranki, Lindsay Garmirian and Diane Damiano

Abstract— **We have developed a vector tissue Doppler imaging (TDI) system based on a clinical scanner that can be used to measure muscle velocities independent of the direction of motion. This method overcomes the limitations of conventional Doppler ultrasound, which can only measure velocity components along the ultrasound beam. In this study, we utilized this method to investigate the rectus femoris muscle velocities during a patellar tendon jerk test. Our goal was to investigate whether the muscle elongation velocities during a brisk tendon tap fall within the normal range of velocities that are expected due to rapid stretch of limb segments. In a preliminary study, we recruited six healthy volunteers (three men and three women) following informed consent. The stretch reflex response to tendon tap was evaluated by measuring: (1) the tapping force using an accelerometer instrumented to the neurological hammer (2) the angular velocities of the knee extension and flexion using a electrogoniometer (3) reflex activation using electromyography (EMG) and (4) muscle elongation, extension and flexion velocities using vector TDI. The passive joint angular velocity was linearly related to the passive muscle elongation velocity (R^2=0.88). The maximum estimated joint angular velocity corresponding to muscle elongation due to tendon tap was less than 8.25 radians/s. This preliminary study demonstrates the feasibility of vector TDI for measuring longitudinal muscle velocities and indicates that the muscle elongation velocities during a clinical tendon tap test are within the normal range of values for rapid limb stretch encountered in daily life. With further refinement, vector TDI could become a powerful method for quantitative evaluation of muscle motion in musculoskeletal disorders.**

Keywords-Ultrasonography, pulsed Doppler, vector Doppler; reflex, stretch; neuromuscular diseases;

I. INTRODUCTION

ALTHOUGH the functional significance of muscle stretch reflexes is not entirely clear, their role in the sensation and control of interactions with the environment is evident [1]. Abnormalities in the reflex response are associated with various movement disorders, for example spasticity developing after stroke, head and spinal cord trauma, cerebral palsy and many other neurological disorders. The standard tendon tap test (for example, the patellar tendon jerk) is a clinical measure of the stretch reflex activity and excitability of the spinal cord. The brisk tendon tap causes a rapid lengthening of the muscle, activation of Ia muscle spindle afferents and reflex monosynaptic activation of the spinal motoneuron pool of the muscle, resulting in the rapid knee extension.

Stimuli like the tendon tap are not encountered during normal movement activities. It is not known whether the muscle lengthening velocity during a tendon tap approaches or exceeds those produced by the rapid stretch of a limb segment, or how it compares to the range of knee angular velocities encountered during functional movements. Therefore, there is some disagreement about the significance of the tendon jerk reflexes (as clinically evaluated) in contributing to the functional limitations of patients with movement disorders [2, 3].

Currently, there is no reliable method to directly measure the muscle elongation and activation velocities. Quantitative methods for assessing the stretch reflex include: measurement of the force of the tendon taps (neurological hammers instrumented with accelerometers), and the biomechanical (electrogoniometers, 3D motion capture, force transducers) and electromyographical (EMG) response to the tendon taps.

Ultrasound imaging can be used to easily and noninvasively visualize muscle motion. Tissue Doppler imaging (TDI) is routinely used for estimating velocities of cardiac muscle and can potentially be used for estimating skeletal muscle velocities as well [4, 5]. Muscle elongation and contraction velocities are often longitudinal along the skin surface. This poses a challenge for conventional Doppler methods, since they can only estimate the velocity component along the direction of the propagating ultrasound beam, which is perpendicular to the skin surface. We have developed a vector TDI system by electronically splitting a linear array transducer into multiple sub-apertures that can be electronically steered to estimate motion in multiple directions and reconstruct both the velocity magnitude and direction in an angle-independent manner. We have implemented this method on a clinical ultrasound instrument with a research interface.

The aim of this preliminary study was to use vector TDI to evaluate the feasibility of:

(1) Measuring rectus femoris muscle longitudinal velocities during a clinical tendon tap test.

(2) Determining the transfer function between the angular knee velocity and longitudinal rectus femoris velocity in healthy individuals.

(3) Using the transfer function to calculate the knee angular velocity corresponding to the tendon tap.

S. Sikdar and A. Eranki are with George Mason University, Fairfax, VA 22030 USA

M. Lebiedowska, L. Garmirian and D. Damiano are with the National Institutes of Health Clinical Center, Bethesda, MD 20892, USA.

Corresponding author: S. Sikdar (phone: 703-993-1539; fax: 703-993-1601; e-mail: ssikdar@ gmu.edu).

978-1-4244-3296-7/09/$25.00 ©2009 IEEE

II. MATERIALS AND METHODS

A. Study Population

Six healthy volunteers (three men and three women, age range 20-29 years) were recruited from the staff and students at George Mason University and provided informed consent to participate in the study. Our Institutional Review Board approved all the study procedures. The tendon tap test was performed on all subjects with simultaneous ultrasound imaging.

B. Tendon tap test

The tendon of the knee quadriceps muscle was tapped multiple times (up to ten, approximately once per second) with a neurological hammer at three levels of manually-controlled force (weak, moderate, strong). The impact hammer, instrumented with an accelerometer (Omega Engineering Inc., Stamford, CT), was used to measure the impact force. The knee angular motion was measured with an electrogoniometer (Biometrics Ltd., U.K.) attached to the knee joint, and the maximum angular velocity of knee extension in response to stretch (ω_{ex}) was measured. The vastus lateralis muscle was instrumented with surface EMG (Motion Lab System Ltd., Baton Rouge, LA). Previous studies have demonstrated that in response to tendon tap, both rectus femoris and vastus lateralis muscles are activated through monosynaptic networks [6].

C. Vector Tissue Doppler Imaging

The vector Doppler method is based on estimating the velocity vector from the measurements taken from two or more independent directions [7]. We have developed a vector Doppler system using a clinical scanner with an array transducer. The array transducer was divided into a transmit sub-aperture and two receive sub-apertures as shown in Fig. 1. Ultrasound is transmitted along a beam normal to the transducer and the receive apertures are steered at an angle relative to the normal. This vector Doppler configuration was implemented on an Ultrasonix SonixRP US system (Richmond, BC, Canada) with a 5-14 MHz linear array probe, L14-5/38 consisting of 128 transducer elements.

The Sonix RP system has a research interface that enables low-level beamforming and pulse sequencing control through a software development kit called Texo. This interface was used for the beam steering and aperture control. For this study, the receive apertures were steered at an angle of 45 degrees. The transmit beam was defocused to increase the region of beam overlap. This was achieved by setting the transmit focus to a depth of 6 cm, which was far from the location of the rectus femoris muscle. B-mode imaging was used to ensure that the center of the rectus femoris muscle was approximately located at the expected the beam overlap region (as shown in Figure 1).

The velocity vector was reconstructed from the individual velocity component following methods described in detail by Dunmire et al. [7]. The velocity was estimated using the conventional autocorrelation method with a correction for the variance (corrected velocity = estimated velocity + standard deviation of velocity).

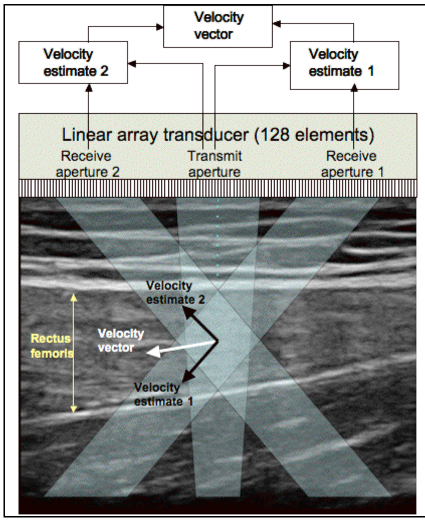

Figure 1. Schematic describing the vector Doppler setup. A linear array ultrasound transducer was split into a transmit sub-aperture and two steered receive sub-apertures. The beams overlap in the region of interest in the rectus femoris muscle. This setup enables the estimation of two independent velocity components for reconstructing the velocity vector.

The velocity estimates were calibrated using a string phantom (CIRS Inc. Norfolk, VA). The string was moved at controllable velocities using a stepper motor connected to a pulley.

The ultrasound data acquisition was synchronized with the instrumented neurological hammer, electrogoniometer and EMG using an external trigger output from the ultrasound system.

D. Data Analysis

The rectus femoris muscle velocities associated with the reflex response to a tendon tap has three peaks as shown in Figure 2(E). The first velocity peak occurs immediately after the hammer impact and corresponds to the elongation of the muscle in response to the tendon tap (v_{el}^{tap}). The second peak occurs after the EMG signal indicating activation of reflex extension and corresponds to the reflex muscle extension velocity (v_{sh}^{reflex}). The third peak is the passive flexion of the knee returning to its original position. The muscle elongation velocity at this instant $v_{el}^{passive}$ coincides with the negative knee angular velocity $\omega_{el}^{passive}$. In Figure 2(E), note that the direction of $v_{el}^{passive}$ is the same as v_{el}^{tap} as expected, and occurs predominantly in the lateral direction (blue trace) along the length of the rectus femoris.

We calculated the transfer function between ($\omega_{el}^{passive}$) and ($v_{el}^{passive}$). The equivalent knee angular velocity (ω_{el}^{tap}) corresponding to the elongation of rectus femoris muscle during standard tendon tap can then be estimated from v_{el}^{tap} as follows:

$$\begin{aligned} &\omega_{el}^{passive} = A \times v_{el}^{passive} + B \\ &\Rightarrow \omega_{el}^{tap} = A \times v_{el}^{tap} + B \end{aligned} \qquad (1)$$

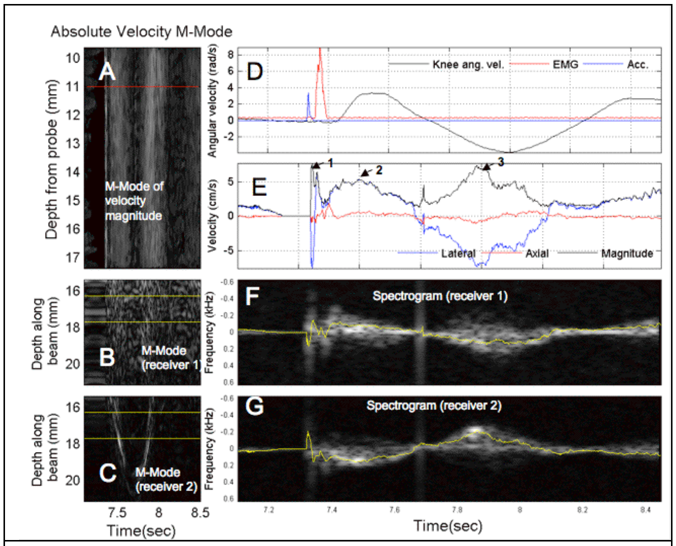

Figure 2. Vector Doppler display. (A) An M-mode display of the estimated velocity magnitude, with time on the horizontal axis and depth on the vertical axis. (B, C) M-mode of the received echoes by receivers 1 and 2, respectively. The yellow lines indicate the region of interest based on the center of the rectus femoris. (D) The joint angular velocity (black), EMG (red) and hammer acceleration signals (blue). (E) The estimated velocity magnitude and the axial (red) and lateral (blue) components. Arrows 1, 2, and 3 represent the elongation, reflex extension and passive flexion velocities. (F, G) Doppler spectrograms of echoes received by receivers 1 and 2, respectively. The yellow lines represent the detected velocities.

III. RESULTS

A. *Validation of the Vector Doppler velocity estimates*

The string phantom was used to calibrate the vector Doppler system. The velocity of the string was estimated for the receive beam steering angle of 45^0 and a region of interest at a depth of 12-16 mm which corresponds to the experimental conditions for our *in vivo* studies. Mean absolute error was 9% in the velocity magnitude estimated using our method compared to the manufacturer specified velocity of the string. The maximum error was 16%. The maximum error using conventional 1D Doppler ultrasound using the same transmit and receive aperture sizes with the string at 60^0 to the transducer was 22%.

B. *Estimation of elongation, reflex extension and passive flexion velocities*

Fig. 2(A) shows an M-mode display of the reconstructed velocity magnitude. The M-mode echoes received by the two receive apertures are shown in (B) and (C), while the corresponding spectrograms are shown in (F) and (G). Fig. 2(E) shows the estimated elongation, extension and flexion velocities. Table 1 summarizes the observed linear regressions between the various measurements and estimated values in this study. The passive elongation velocity of the rectus femoris muscle measured using vector TDI correlated with the angular velocity of the knee joint measured using the electrogoniometer (Fig. 3(A), R^2=0.88). The estimated joint angular velocity corresponding to the muscle elongation due to tendon tap was less than 8.25 radians/s (Fig. 3(B)). Some cases had high sensitivity to tendon tap, with a high correlation between muscle elongation and hammer acceleration (R^2 =0.71 and 0.96, for cases 4 and 5 respectively), whereas other cases had lower sensitivity (R^2 =0.03, 0.33, 0.25 and 0.56, for cases 1,2,3 and 6 respectively).

Table 1. Correlations between the different variables.

Variables	R^2	Linear regression
$\omega_{el}^{passive}$ and $v_{el}^{passive}$	0.88	$\omega_{el}^{passive} = 0.63 \times v_{el}^{passive} - 0.33$
$v_{el}^{passive}$ and $v_{ex}^{passive}$	0.80	$v_{el}^{passive} = 1.14 \times v_{ex}^{passive}$
EMG and v_{sh}^{reflex}	0.70	$EMG = 0.11 \times v_{sh}^{reflex} - 0.17$

IV. DISCUSSION

In this study, a novel vector TDI method was used to measure the rectus femoris muscle velocities during the monosynaptic stretch reflex response elicited by a patellar tendon tap. The direct measurement of the muscle velocity during elongation enabled us to estimate the joint angular velocity that is equivalent to the muscle stretch produced by the patellar tendon jerk. Our preliminary results indicate that the maximum joint angular velocity corresponding to tendon tap elongation is less than 8.5 radians/s, which is well within the normal range of angular velocities for the knee joint (up to 12 radians/s) [8].

Grubb *et. al.* [5] measured the peak contraction velocities in the rectus femoris during a tendon tap test using the TDI M-mode available on conventional echocardiography systems. They measured peak contraction velocities of 5.6±1.3 cm/s to 8.1±1.6 cm/s in five subjects, which are comparable to the range of velocities measured in our study.

Some limitations of this study must be acknowledged. Although Doppler methods are widely used clinically for the measurement of velocities, various factors affect the accuracy of Doppler velocity measurements. The Doppler signal undergoes spectral broadening due to the geometry of the ultrasound beam as well as due to acceleration and deceleration of the scatterer (as shown in Fig.2 (D) and (E)). Spectral broadening increases the variance of Doppler estimates computed using conventional narrowband spectral estimators, such as Fourier transform and autocorrelation. The spectral broadening is especially high for transient velocities with high acceleration or deceleration, which is the case for the muscle elongation velocity in response to a tendon tap. We included a variance correction term in our velocity estimate, so that the velocity estimates were close to the maximum Doppler shift frequencies. However, it is still possible that the muscle elongation velocities are somewhat underestimated in the present study. Broadband spectral estimators, such as the 2D Fourier transform, that make use of the full bandwidth of the received signal can decrease the variance of the estimate. In addition, time-frequency methods can improve the accuracy of measuring transient velocities. We will investigate these refinements in future studies. However, based on the maximum observed Doppler shifts for muscle elongation in our study, we believe that the maximum joint angular velocity equivalent to tendon tap is still within the normal range of angular velocities of the knee.

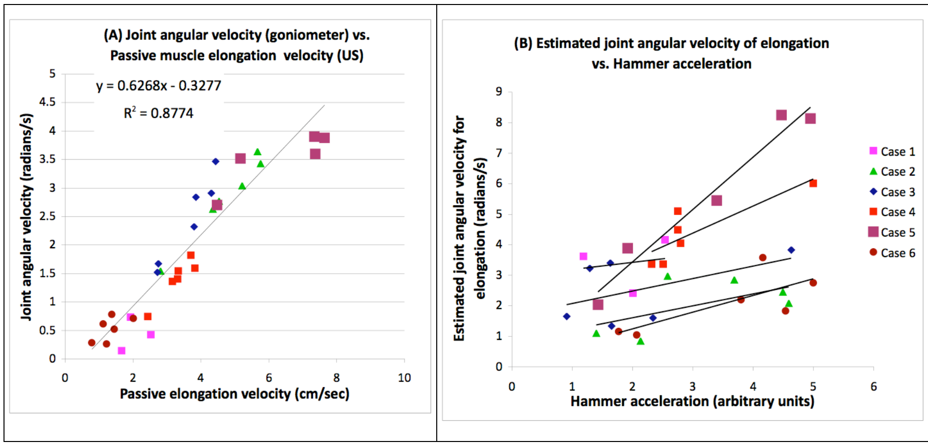

Figure 3. (A) The transfer function between the measured passive joint angular velocity using a goniometer, $\omega_{el}^{passive}$, and the passive muscle elongation velocity measured using US, $v_{el}^{passive}$. (B) The estimated joint angular velocity equivalent to the elongation produced by tendon tap, ω_{el}^{tap}, for different cases and different tapping strengths. Some cases had higher sensitivity to tendon tap, with a high correlation between ω_{el}^{tap} and the hammer acceleration (R^2 =0.71 and 0.96, for cases 4 and 5 respectively), whereas other cases had lower sensitivity (R^2 =0.03, 0.33, 0.25 and 0.56, for cases 1,2,3 and 6 respectively).

In our studies, the ultrasound transducer was externally clamped and the subject was seated on a fixed surface to minimize relative motion between the knee joint and the ultrasound probe due to the knee jerk. However, some relative motion was unavoidable. We believe that the impact of such relative motion on our measurements was minimal, since we are measuring instantaneous muscle velocity. In the future, our methods can be extended to study more complex movements, as well as simultaneous measurement of the velocities of multiple muscle groups.

Other researchers have used ultrasound to measure fascicle stretch velocities during stretch reflex response [9] [10]. Typically, these methods involved the measurement and tracking of the fascicle length using B-mode ultrasound. This method has several limitations since the entire fascicle length for many muscle groups is difficult to measure due to the limited field of view of ultrasound and the measurements are sensitive to any movement of the transducer. The Doppler method overcomes these limitations since we are measuring the instantaneous velocity at a specified location without any need to visualize the entire fascicle.

Conventional Doppler ultrasound can only estimate velocity components along the direction of propagation of the ultrasound beam. It is difficult to ensure a constant angle of the muscle velocity vector relative to the transducer during muscle contraction or relaxation. Furthermore, most muscle motion occurs longitudinally along the skin surface, while ultrasound is typically transmitted perpendicular to the skin surface. Therefore, conventional Doppler has limited utility for the estimation of muscle velocities. Vector TDI overcomes this limitation. We have successfully demonstrated that vector Doppler is capable of estimating longitudinal muscle velocities. While other researchers have developed custom vector Doppler instruments for blood flow imaging, a significant advantage of our approach is the use of a clinical ultrasound instrument, which would facilitate translation to clinical practice.

V. CONCLUSION

We have developed a vector TDI system based on a clinical ultrasound scanner for measuring longitudinal muscle velocities. This study demonstrates the feasibility of vector TDI for measuring longitudinal muscle velocities during a monosynaptic stretch reflex response. Preliminary results indicate that the muscle elongation velocities during a clinical tendon tap test are within the normal range of values for rapid limb stretch encountered in daily life. With further refinement, the vector TDI method could become a powerful tool for evaluation of muscle motion in musculoskeletal disorders.

REFERENCES

[1] P. B. Matthews, “Restoring balance to the reflex actions of the muscle spindle: the secondary endings also matter,” *J Physiol,* vol. 572, pp. 309-10, 2006.

[2] V. Dietz, “Role of peripheral afferents and spinal reflexes in normal and impaired human locomotion,” *Rev Neurol (Paris),* vol. 143, pp. 241-54, 1987.

[3] D. M. Corcos, G. L. Gottlieb, R. D. Penn *et al.*, “Movement deficits caused by hyperexcitable stretch reflexes in spastic humans,” *Brain,* vol. 109 (Pt 5), pp. 1043-58, 1986.

[4] N. Pulkovski, P. Schenk, N. A. Maffiuletti *et al.*, “Tissue Doppler imaging for detecting onset of muscle activity,” *Muscle Nerve,* vol. 37, pp. 638-49, 2008.

[5] N. R. Grubb, A. Fleming, G. R. Sutherland *et al.*, “Skeletal muscle contraction in healthy volunteers: assessment with Doppler tissue imaging,” *Radiology,* vol. 194, pp. 837-42, 1995.

[6] J. D. Brooke, and W. E. McIlroy, “Movement modulation of a short latency reflex linking the lower leg and the knee extensor muscles in humans,” *Electroencephalogr Clin Neurophysiol,* vol. 75, pp. 64-74, 1990.

[7] B. Dunmire, K. W. Beach, K. Labs *et al.*, “Cross-beam vector Doppler ultrasound for angle-independent velocity measurements,” *Ultrasound Med Biol,* vol. 26, pp. 1213-35, 2000.

[8] M. E. Houston, R. W. Norman, and E. A. Froese, “Mechanical measures during maximal velocity knee extension exercise and their relation to fibre composition of the human vastus lateralis muscle,” *Eur J Appl Physiol Occup Physiol,* vol. 58, pp. 1-7, 1988.

[9] N. J. Cronin, J. Peltonen, M. Ishikawa *et al.*, “Effects of contraction intensity on muscle fascicle and stretch reflex behavior in the human triceps surae,” *J Appl Physiol,* vol. 105, pp. 226-32, 2008.

[10] K. Nakazawa, S. I. Yamamoto, T. Ohtsuki *et al.*, “Neural control: novel evaluation of stretch reflex sensitivity,” *Acta Physiol Scand,* vol. 172, pp. 257-68, 2001.