Ultrasound Strain Rate Imaging of Individual Muscle Motor Units

Max Heger[1], Øyvind Stavdahl[1], and Hans Torp[2]

[1]Department of Engineering Cybernetics, Norwegian Univ. of Science and Technology, Trondheim
[2]Department of Circulation and Medical Imaging, Norwegian Univ. of Science and Technology, Trondheim

***Abstract*—Skeletal muscle is organized in motor units, each comprising a motor neuron and all its connected muscle fibres. The arrival of an action potential (a neural "impulse") causes the fibers to contract, they exhibit a *twitch*. This study aimed for the spatiotemporal detection of individual twitches, which may allow for a more detailed real-time study of muscle physiology and higher fidelity in applications such as prosthesis control.**

We used a commercial ultrasound scanner and a linear probe in a clamped and fixed position over the biceps, with the image plane perpendicular to the muscle fibers. The strain rate scans were made with a frequency of 15MHz and a frame rate of approximately 215 FPS. Recordings of tiny voluntary isometric muscle contractions were made, with ElectroMyoGraphic (EMG) electrodes placed on each side of the probe to detect the associated Motor Unit Action Potentials (MUAPs). The recordings were analyzed using the scanner's Quantitative analysis (Q-analysis) tool for measuring strain rates within selected Regions Of Interest (ROIs).

The results indicate that it is possible to image the mechanical response of a single motor unit by using ultrasonic strain rate imaging. This technique could thus be a future supplement to EMG in certain applications.

***Index Terms*—Action potential, Motor unit, Strain rate ultrasound, Twitch.**

I. Introduction

THE study of human motor control and estimation of motor intent is of great relevance for diagnostics, treatment and rehabilitation of many pathological conditions including limb amputation. For decades, surface electromyography (sEMG) has been a predominant technique for many applications, because it reveals aspects of muscle contractions through the application of external electrodes and relatively simple instrumentation. However, the technique has some severe limitations, one being its lack of spatial specificity [1]. This calls for alternative methods in the study of skeletal muscle activation.

In 1997, ultrasound imaging was proposed as a possible solution by Stavdahl et al. [2] who demonstrated how, under ideal conditions, isometric contraction force can be derived from ultrasound pulse-echo data. Their intended application was the control of externally powered upper-limb prostheses, but the technology was deemed to be too immature at the time. More recently, [3], [4] and [5] have explored this possibility further in both normal subjects and amputees, referring to the method as sonomyography (SMG). As in [2], these authors focused on dynamic thickness changes of skeletal muscles during contraction, but during joint movements rather than under isometric conditions. They found that SMG might perform better than EMG as a method for prosthetic control.

The present project was initiated in order to exploit more sophisticated aspects of ultrasound imaging and recent instrument developments, as we believe this can reveal more information about the "inner life" of muscle tissue than what can be derived from a one-dimensional thickness measurement. In particular, if ultrasound can be used e.g. to image individual motor units, it can contribute to a more explicit study of muscle physiology during contraction and to a more dexterous methods for prosthesis control.

A. Muscle innervation

The nervous system is responsible for distributing signals throughout the body. Skeletal muscles are under voluntary control and gets innervated by somatic motor neurons that are connected to muscle fibers through neuromuscular junctions (Fig. 1). A somatic motor neuron contains several axon terminals, each connected to a muscle fiber. A single somatic motor neuron and all the muscle fibers it innervates collectively constitute a motor unit. To be able to move the body in a smooth and controlled manner, different motor units are stimulated rapidly and asynchronously. The recruitment of motor units follows the so-called "size-principle": as more force is needed, gradually larger motor units are innervated, and stimulated with higher frequency.

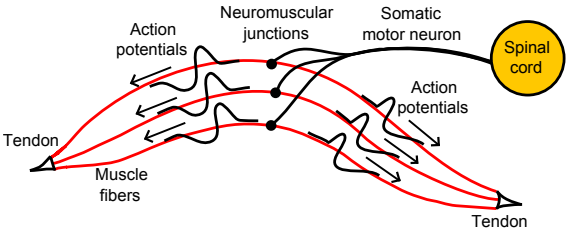

Fig. 1. Motor unit action potential propagation

Neural impulses, or action potentials, are transient displacements of the electrical potential across neural or muscle fiber membranes. When an action potential reaches the neuromuscular junction, it propagates along the muscle fiber membrane (Fig. 1). The muscle fibers in a motor unit are not necessarily adjacent to each other, but are spread in an area known as the motor unit territory (MUT), which typically is 5-10 mm in diameter [6].

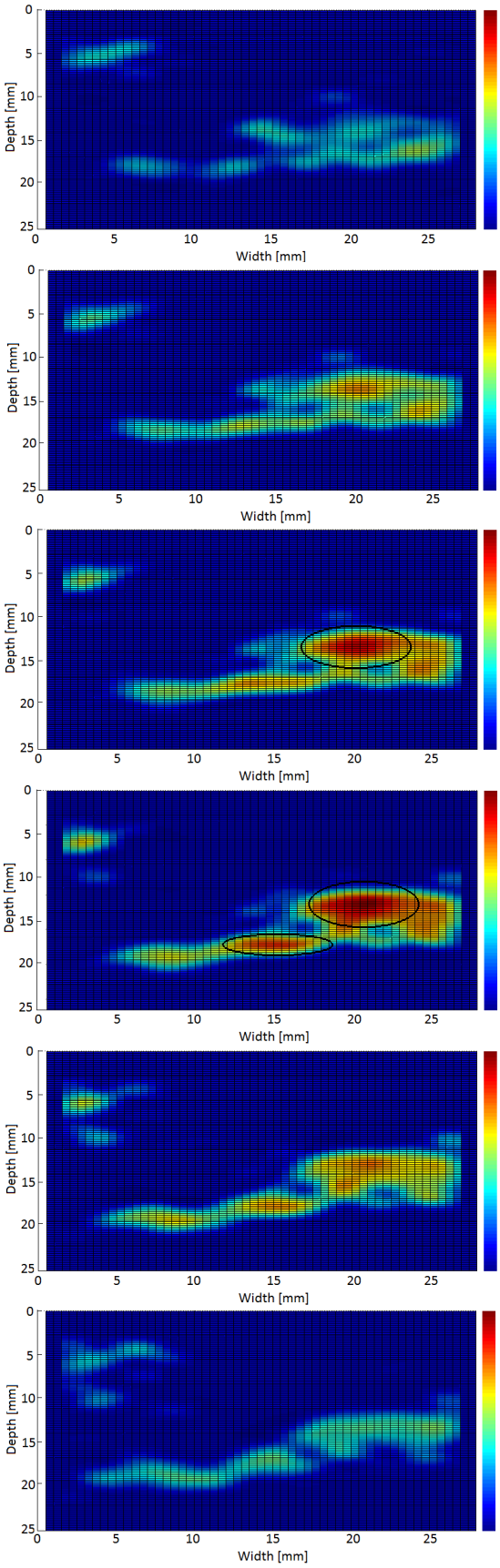

Fig. 2. Six strain rate images showing different frames during a contraction, captured approximately 20 ms apart (cf. Fig. 2). Image 3 and 4 from the top contains encircled regions, marking signs of local expansions.

The combined electrical potential from all active muscle fibers in a motor unit is called the motor unit action potential (MUAP), and it is the combined MUAPs from all active motor units that constitute the EMG signal. The mechanical response of a motor unit to a single MUAP is called a twitch. In an ultrasound sequence, a twitch is hence expected to be seen as a local expansion followed by a contraction in the image plane, because during each twitch the active fibers will temporarily be shortened and thickened. Fig. 2 shows a preliminary sequence of six consecutive ultrasound strain rate images during a contraction. The blue regions indicate a strain rate of zero, while the green, yellow and red regions indicate increasingly positive strain rate. This sequence was captured by an GE Vingmed Vivid E9 ultrasound scanner and loaded into MATLAB for computation of strain rate. Fig. 3 shows the corresponding sEMG signal captured at the site of the ultrasound probe, with vertical lines marking time steps corresponding to the six images in Fig. 2.

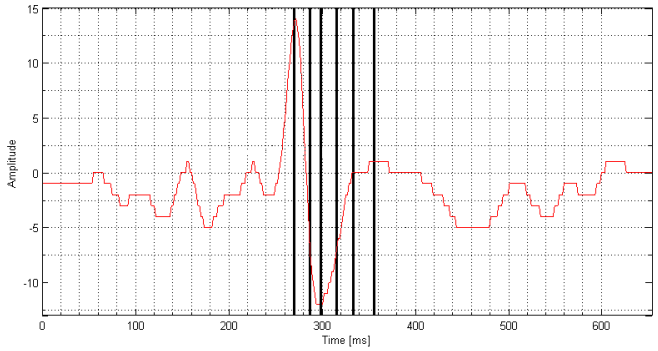

Fig. 3. EMG signal of a muscle contraction. The vertical lines sequentially marks the times of the strain rate images in Fig. 2. from top to bottom.

The EMG signal varies depending on which motor units are activated at any given time, as MUAPs from different motor units exhibit different shape and amplitude. The captured EMG signal usually contains the superposition of multiple MUAPs, and it is then difficult to differentiate the contributions of individual motor units. However, if the contraction is very weak, the action potentials occur more or less separated in time, and it is possible to identify which MUAPs stem from the same motor unit. Nevertheless, since EMG is a one-dimensional signal, one will frequently observe MUAPs that overlap to some degree. As seen on the EMG signal (bottom blue graph) in Fig. 5 and 6, there are indications of 1 and 2 action potentials, respectively. Each of these three action potentials are different with respect to shape and amplitude. The first action potential in Fig. 6 and the action potential in Fig. 5 may stem from a single motor unit (MUAPs), but the last action potential in Fig. 6 contains the superposition of multiple MUAPs.

The aim of this study is to determine whether ultrasound imaging can be used to locate individual motor units in space and time. If this is possible, it will provide an unique "window" into the inner life of a contracting skeletal muscle at a level that can hardly be achieved through EMG measurements. Specifically, the possibility of observing contractions both in

time and space will dramatically increase the separability of individual MUAPs; we do not only know *when*, but also *where* a twitch occurs.

II. Methodology

A. Test setup

The test setup was designed to get the highest possible frame rate with a sufficient resolution to locate small morphological changes in muscle tissue on the size of the MUT. The experiments were carried out by the use of a GE Vingmed Vivid E9 ultrasound scanner and a linear ML6-15 probe. The probe was placed in a clamped, fixed position below the innervation zone on the anterior side of the upper arm, giving images perpendicular to the muscle fibers in the biceps (Fig. 4).

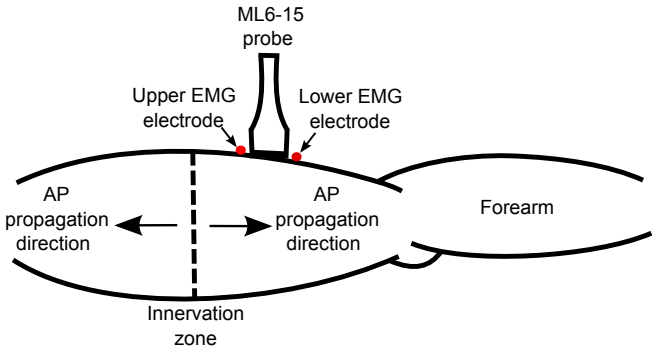

Fig. 4. Experimental setup showing the ultrasound probe and the placement of the ultrasound probe and EMG electrodes.

The scans were carried out in "Strain rate"-mode in the test option "msc TVI" with a frequency of 15MHz and a frame rate of approximately 215 FPS. Recordings of voluntary isometric muscle contractions were made, with passive EMG electrodes placed on each side of the probe to detect MUAPs (Fig. 4). The electrodes were connected to the scanner's ECG input terminals to allow synchronous EMG and ultrasound data acquisition.

In the analysis of strain rate response, there were indications of a delay between the muscle response captured by the EMG electrodes and the tissue Doppler data. This can be attributed to three different causes:

- MUAP propagation delay: One EMG electrode is placed closer to the innervation zone than the probe, which results in a delay caused by the finite propagation velocity of the action potential in muscle fibers (3-5 $\frac{m}{s}$ [7]).
- Mechanical delay: The intrinsic delay of the muscle, i.e. the time from MAUP arrival to the registration of force (1.1 ms [8]).
- Electrical delay: Any additional delay introduced by the scanner hardware and software.

A separate test setup was chosen to measure the electrical delay. This setup consisted of the same equipment as before, but instead of testing on a human subject, a bucket filled with water was used. One EMG electrode was aligned with the footprint on the ML6-15 probe and attached with tape, while the two other EMG electrodes were placed in the bucket (one electrode for signal ground). The probe footprint was then submerged in water, giving an immediate response in both the EMG and ultrasound data at the moment the instrument touched the water surface. The ultrasound and EMG data from 30 different trials at frame rates between 125 to 222 FPS were loaded into Matlab for computation of the electrical delay. The delay was found to be independent of frame rate and was measured to be 5±3 ms.

The upper EMG electrode was placed approximately 2.5 cm from the center of the probe, which results in a MUAP propagation delay of approximately 6.7±1.7 ms. This indicates that the ultrasound response is expected to be seen 12.8±4.7 ms after the EMG response.

B. Testing and analysis

To be able to determine if ultrasound can be used to image individual motor units, the aim was to acquire a data sequence containing multiple MUAPs of different shape, to see if different motor units (as indicated by their different positions in the image) in this case are indeed active during the different MUAPs.

The analysis was performed using the scanner's quantitative analysis (Q-analysis) tool for measuring strain rates inside elliptical regions of interest. Potential motor units were found by searching for typical motor unit behavior, a locally positive strain rate (associated with the spatial expansion of the motor unit in the image plane) followed by a decreasing strain rate (relaxation).

III. Results

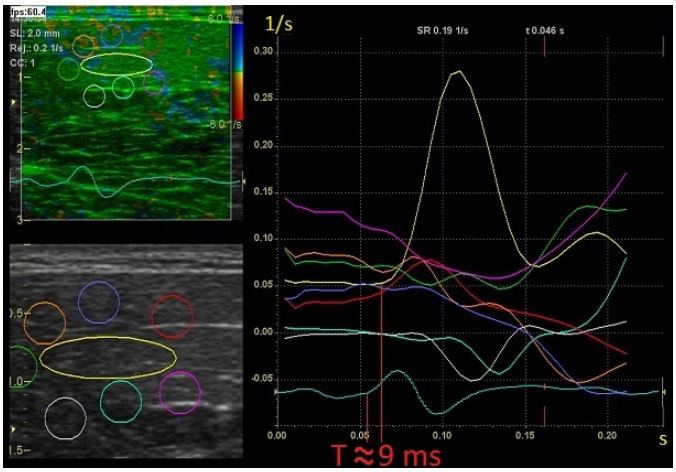

Fig. 5. Q-analysis of sequence containing one MUAP. The graph on the right hand side shows strain rate ($\frac{1}{s}$) at a given time (s).

Figure 5 shows a screen capture of the Q-analysis tool. The right hand side window shows strain rate graphs, where each colored graph is the mean strain rate inside the ROI of equal color in the two windows to the left. The upper left window shows strain rate in the entire scan region, while the lower left window shows a B-mode image of a part of the scan region.

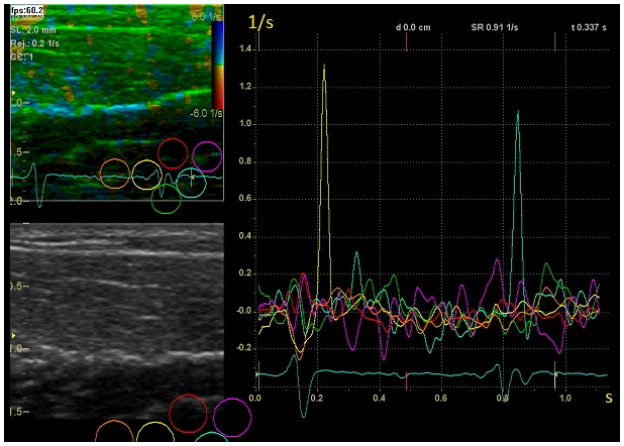

Fig. 6. Q-analysis of sequence containing two distinct MUAPs. In the Q-analysis window, the B-mode images (bottom left corner) does not show the entire scan region, so some of the chosen ROIs are excluded.

The recorded sequence contains one contraction, as indicated by the single MUAP in the EMG signal (the lower blue graph in the right side window). In the restricted scanned region of 3x3 cm, the yellow elliptical region was the only region showing signs of expansion.

Figure 6 shows a Q-analysis of a sequence containing two different MUAPs, shown in the lower blue graph (EMG line) in the right side window. Six different ROIs are chosen in this image and only two of these ROIs indicates expansion, namely those in the blue and the yellow circles.

IV. Discussion

It is difficult to measure the time delay between EMG and ultrasound response by looking at Fig. 5, due to the smooth transition between the stationary and the transient phases. A time delay of approximately 9 ms is marked in the figure, which is consistent with the measured expected time delay of 12.8 ± 4.7 ms. The same goes for the delays observed in Fig. 6. The response of the yellow graph in Fig. 6 indicates that the muscle response is slower during the first contraction, but by comparing the time delay between the local maxima of the EMG signals and the strain rate responses in Fig. 5 and 6, the time delay varies between 60 and 100 ms, so the delays in the mechanical responses are of the similar magnitude.

Since the scan was performed on a 3x3 cm section of the upper arm, the entire muscle is not captured in this recording, so there may be muscle activity outside the regions shown in Fig. 5 and 6. This means that the electrical potential seen on the EMG line may be a combination of multiple MUAPs or may stem from activity outside the presented section. However, as the MUAP amplitude detected by electrodes will drop dramatically as the distance to the active tissue increases, this contribution is believed to be negligible. Also contributing to this conclusion is the fact that the region marked by the yellow ellipse exhibits significant expansion that is clearly correlated with the recorded MUAP, while all the surrounding regions show little or no such deformation.

It is also difficult to conclude that there is only one active motor unit by looking at the Q-analysis window in Fig. 5. The yellow region is within the size of the MUT (5 to 10 mm), but there may be overlapping motor units inside this region. Considering the asynchronous nature of motor unit recruitment, however, this is also deemed unlikely. Furthermore, even if this was in fact a case of simultaneously firing and collocated motor units, this does not jeopardize our main findings and conclusions.

The two MUAPs in Fig. 6 are clearly distinguishable, and as seen in the strain rate graphs, the first MUAP is accompanied by a local contraction mainly in the yellow region while the second is followed by mechanical activity mainly in the blue region.

Like in Fig. 5, Fig. 6 only includes a part of the muscle and there may be expansion in other regions, so the captured MUAPs may be caused by multiple motor units. The ROIs in this image are only 3 mm in diameter, so there may be a couple of muscle fibers belonging to the present motor units that have not been captured in this image. But the fact that two separate regions are active during different MUAPs strengthens the hypothesis that the morphological changes detected in the yellow and blue regions are associated with distinct motor units.

The technique's applicability to stronger muscle contractions, where twitches may overlap both in time and space, remains to be investigated.

V. Conclusion

The results indicate that it is possible to image the mechanical response of a single motor unit by using ultrasonic strain rate imaging during tiny voluntary isometric contractions. This may provide an optimal starting point for any system or algorithm aiming at estimating the person's motor intention at a detailed level, because motor activity can be attributed to specific muscles within a muscle group or to specific segments within a single muscle. This technique could thus contribute to a more explicit study of muscle physiology during contraction and be a future supplement to EMG in certain applications.

References

[1] M. Zecca, S. Micera, M.C. Carrozza and P. Dario, *Control of Multifunctional Prosthetic Hands by Processing the Electromyographic Signal*, Critical Reviews in Biomedical Engineering, Vol 30, p.459-p.485, 2002.

[2] Øyvind Stavdahl, Aage Gronningsaeter and Kjell E Malvig, *Ultrasound Based Estimation of Muscle Contraction*, Institute of Biomedical Engineering, University of New Brunswick, MEC '97 "Issues in Upper Limb Prosthetics", 1997.

[3] Y.P. Zheng, M.M.F. Chan, J. Shim X. Chen and Q.H. Huang, *Sonomyography: Monitoring Morphological Changes of Forearm Muscles in Actions with the Feasibility for the Control of Powered Prosthesis*, Medical Engineeing & Physics, Vol 28, p.405-p.415, 2006

[4] Jing-Yi Guo, Yong-Ping Zheng, Qing-Hua Huang, Xin Chen, Jun-Feng He and Helen Lai-Wa Chan, *Performances of one-dimensional sonomyography and surface electromyography in tracking guided patterns of wrist extension*, Ultrasound in Med. & Biol., Vol 35, p.894-p.902, 2009.

[5] Xin Chen, Yong-Ping Zheng, Jing-Yi Guo and Jun Shi, *Sonomyography (SMG) control for powered prosthetic hand: a study with normal subjects*, Ultrasound in Med. & Biol., Vol 36, p.1076-p.1088, 2010.

[6] Paul E. Barkhaus and Sanjeev D. Nandedkar, *EMG evaluation of the Motor Unit - Electrophysiologic Biopsy*, Medscape, Last update: 2013.

[7] Gerald E. Loeb and Claude Ghez, *The Motor Unit and Muscle Action*, Book (Kandel): Principles of Neural Science, p. 676.

[8] E.M. Winter and F.B.C. Brookes, *Electromechanical response times and muscle elasticity in men and women*, Eur J Appl. Physiol., Vol 63, p.124-p.128, 1991.