The Effect of Subcutaneous Fat on

Myoelectric Signal Amplitude and Cross-Talk

T. A. Kuiken*/**, M. M. Lowery* and N. S. Stoykov*

Foot note (Affiliations and financial acknowledgements):

* Rehabilitation Institute of Chicago, the Dept. of PM&R at Northwestern University Medical School, Chicago, Illinois, USA.

** The Electrical and Computer Engineering Dept. of Northwestern University, Evanston, Illinois, USA.

Corresponding Author:

Todd Kuiken, MD, PhD
Rehabilitation Institute of Chicago, Rm. 1124
345 E. Superior St.
Chicago, IL 60611
Tel: 312-238-8072
Fax: 312-238-1166
Email: tkuiken@rehabchicago.org

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Abstract

The effect of subcutaneous fat on myoelectric signal amplitude and cross-talk was studied using finite element (FE) models of electromyogram (EMG) signal propagation. A FE model of the upper arm consisted of skin, fat, muscle and bone tissues in concentric layers. Single muscle fiber action potentials were simulated for muscle fibers at a variety of depths and combined to simulate surface EMG interference patterns. As fat layers of 3, 9 and 18 mm were added to the model, the RMS (root mean square) amplitude of the surface EMG signal directly above the center of the active muscle decreased by 31.3, 80.2 and 90.0 %, respectively. Similarly, surface EMG cross-talk above the region of inactive muscle increased as the fat layer thickness increased. The surface EMG RMS amplitude fell below 5% of it’s value above the center of the muscle at 14°, 17°, 34° and 47° from the edge of the active muscle with fat layers of 0, 3, 9 and 18 mm, respectively. An additional model was developed with the subcutaneous fat layer thinned from 9 mm to 3 mm in a small, focal region under a pair of recording electrodes. Reducing the fat layer in this manner caused the surface EMG amplitude at the electrodes to increase by 241% and decreased the EMG cross-talk by 68%; this was near the values for the 3 mm uniform fat layer. This demonstrates that fat reduction surgery can increase surface EMG signal amplitude and signal independence for improved prosthesis control.

Introduction

The surface electromyogram (EMG) is the most commonly used signal for the control of externally powered prostheses. The quality of the surface EMG as a control signal is dependent on its amplitude and on cross-talk from surrounding muscles. EMG cross-talk may be defined as the unwanted detection of volume conducted signals from muscles other than the muscle of
interest (De Luca and Merletti, 1988). For example, if an extensor muscle contracts causing an EMG signal to be detected at an electrode over a flexor muscle, the extensor signal recorded over the flexor muscle is known as myoelectric cross-talk. Clearly large amounts of EMG cross-talk can interfere with the operation of a myoelectric prosthesis. The amplitude of the myoelectric signal must be sufficiently large so that the surface EMG can be easily detected and separated from background noise.

Subcutaneous fat has a negative impact on both surface EMG signal amplitude and on cross-talk. Subcutaneous fat tissue increases the separation between the electrical source (the muscle fibers) and the recording electrodes, resulting in increased spatial filtering of the EMG signal and hence a decrease in surface EMG amplitude (Lindstrom and Magnusson, 1977; Lowery et al., 2002a). Similarly, cross-talk has been observed to increase with subcutaneous fat thickness (Solomonow et al. 1994; De La Barerra and Milner, 1994). Increasing quantities of subcutaneous fat tissue reduces the relative differences in the distances between the muscle fibers of interest and the electrodes located above the different muscles, causing the action potentials to appear more similar at each electrode (Lowery et al., 2002a).

Since the presence of subcutaneous fat causes surface EMG signal amplitude to decrease and cross-talk to increase, then thinning the subcutaneous fat layer should improve the quality of the myoelectric signal, in terms of both signal power and the independence of signals from neighboring muscles. We hypothesize, therefore, that thinning the subcutaneous fat layer in a small area underneath a recording electrode with a simple surgical procedure, such as liposuction, will increase the amplitude of the surface EMG signal and reduce cross-talk from nearby muscles.
In this paper, we present a finite element (FE) analysis of the effect of subcutaneous fat on surface EMG signal amplitude and cross-talk. FE analysis allows complex geometries to be modelled and realistic diffuse muscle activation to be simulated. There are three specific goals of this paper. The first is to obtain an estimate of how much subcutaneous fat decreases surface EMG amplitude. This is done by simulating diffuse muscle activation with motor units distributed throughout the muscle tissue. The second goal is to estimate how much subcutaneous fat increases cross-talk; also using realistic diffuse activation of the muscle tissue. Finally, the hypotheses will be tested that thinning subcutaneous fat in a small region under a surface electrode will increase the amplitude of the surface EMG signal amplitude and will decrease cross-talk from nearby muscles.

Methods

A finite element model of the human upper arm was created with concentric layers of skin, fat, muscle and bone. For details of the model development see Lowery et al., 2002a&b. Briefly, a cylindrical bone of radius 10 mm was placed at the centre of each model and was surrounded by a cylinder of muscle tissue, radius 40 mm. A layer of subcutaneous fat tissue was placed around the muscle tissue and this was covered with a layer of skin, 1.3 mm thick (Snyder et al., 1974). Biceps skin-fold thickness has been reported to range from 4-45 mm with a mean of $7.1 \pm 4.1$ mm in men and $15 \pm 10$ mm in women aged between 30 and 39 years (Durnin and Wormersley, 1974). The fat layer over the triceps is approximately 50% thicker. Therefore, subcutaneous fat layers 0 mm, 3 mm, 9 mm and 18 mm thick were simulated.

The surface of the arm model was first covered in a uniform, high-resolution rectangular mesh, then the interior of the model was meshed with tetrahedral elements (0.05-15 mm). The
muscle tissue was assumed to be cylindrically anisotropic with an anisotropy ration of 5 (Andreassen and Rosenfalck, 1981; Gielen et al., 1984). Skin, fat, muscle and bone were assumed to be purely resistive, with conductivity values based on those reported in Gabriel et al. (1996). Muscle fiber action potentials were simulated by applying a transmembrane current as described by Rosenfalck (1969) to the surface of a muscle fibre, radius 50 \( \mu \text{m} \), located within the muscle tissue. The FE model was meshed and solved using the EMAS software package (Ansoft Corp., Pittsburgh, PA 15219, USA). FE model parameters are summarized in Table 1.

Motor unit action potentials (MUAP) were obtained by summing together 500 single fibre action potentials, located at the centre of the motor unit territory. A database of MUAPs were simulated for subcutaneous fat layers 0 mm, 3 mm, 9 mm and 18 mm thick. To simulate voluntary surface EMG activity, 400 identical motor units were randomly located throughout the muscle tissue, Fig. 1. The motor units were simulated to fire repetitively with mean firing rates that ranged from 15-25 Hz. The intervals between successive firings of a motor unit, the inter-pulse intervals, were simulated to have a Gaussian distribution about the mean inter-pulse interval (Clamann, 1969). Data was generated for bipolar electrodes separated by an inter-electrode distance of 20 mm, located at intervals of 7.5 degrees around the surface of the model. The root-mean-square (RMS) value of the surface EMG signal at each electrode over an epoch of duration 1 s was calculated. The data presented is the average of 100 simulations, each with a different random motor unit distribution.

To simulate subcutaneous fat reduction in a localized area, the fat layer was thinned in two regions 45 degrees apart shown in Fig. 2. A hemicylindrical section of fat with a radius of 6 mm was removed from a model with a 9 mm subcutaneous fat layer. This effectively thinned the 9 mm fat layer to 3 mm at these two locations. A single muscle fiber source was simulated at a
depth of 10 mm below the surface of the muscle. Diffuse activation could not be readily simulated because the model was no longer perfectly round and symmetrical.

**Results**

A sample EMG interference pattern due to the simultaneous activation of all motor units is presented in Fig. 3. The affect of subcutaneous fat thickness on the amplitude of the surface EMG signal is shown in Fig. 4. In Figure 4 the amplitude of each surface EMG signal is normalized with respect to the RMS amplitude calculated at the electrode directly above the center of the active muscle, in the model with no subcutaneous fat. The addition of subcutaneous fat layers 3, 9 and 18 mm thick caused a reduction in the surface EMG RMS value, directly above the center of the active muscle, of 31.3 %, 80.2 % and 90.0 % respectively. The subcutaneous fat layer acts as a spatial filter, increasing the distance between electrode and source and thus smoothing the surface potential over the region of active muscle and reducing the amplitude of the surface EMG.

As the subcutaneous fat thickness was increased, the falloff in the amplitude of the surface potential around the surface of the model slowed down. As a result, cross-talk over the inactive muscle region increased. In Fig. 5 the surface EMG cross-talk, defined as the ratio of the RMS amplitude of the volume conducted EMG signal to the RMS value of the surface EMG signal above the active muscle, is compared at different electrode sites around the limb, for different values of subcutaneous fat thickness. Cross-talk decayed to 5% of the maximum surface EMG RMS value at 14, 17, 34 and 47 degrees from the edge of the active muscle with subcutaneous fat layers 0, 3, 9, and 18 mm thick, respectively.
The results of the fat reduction simulation are summarized in Table 2. When the subcutaneous fat layer was thinned from a uniform 9 mm thickness to 3 mm in a small area, the surface EMG amplitude increased by 241%, comparable to the amplitude with a uniform 3 mm fat thickness. Similarly, EMG cross-talk decreased by 68% at a site 45° away, almost to the level observed with a uniform 3 mm fat thickness layer.

**Discussion**

Subcutaneous fat substantially reduced the amplitude of the simulated surface EMG over the active muscle. While this result is intuitively to be expected, the magnitude of the effect and the difficulties which is presents in terms of myoelectric control are of note. With a ‘typical’ fat layer thickness of 9 mm above the biceps muscle (Durnin and Wormersley, 1974) the amplitude of the surface EMG fell by 80.2%. For an 18 mm fat layer thickness, which still represents a relatively common thickness for many individuals, the surface EMG was an order of magnitude smaller. These findings are consistent with experimental results and our clinical findings. Hemingway et al, 1995 found that the greater the thickness of subcutaneous tissue between the surface recording site and the contracting muscles, the lower the recorded electromyographic activity. Clinically, we also find that the surface EMG amplitude tends to be smaller in obese people. Furthermore, posterior recording from the triceps tends to produce smaller surface EMG signals than recording over the biceps. This is likely due to the fact that the subcutaneous fat layer is 50% thicker over the posterior triceps than it is over the biceps.

Subcutaneous fat also caused an increase in cross-talk over neighboring muscle regions. With standard myoelectric prosthesis signal processing techniques cross-talk is managed by setting a threshold. The surface EMG must be higher then a given threshold to activate the
control, thus the cross-talk from surrounding muscles must be lower than this threshold. There is no data currently available as to how high this threshold should be and thus how much cross-talk is acceptable. Clearly, the higher the threshold, the harder it is to operate the prosthesis. Furthermore, ergonomic studies suggest that continuous forces less than 15% of maximal voluntary contraction (MVC) will not fatigue the muscle (Muller, 1965). Therefore, we set our goal at reducing cross-talk from other muscles to less than 5% MVC, i.e. the maximum EMG amplitude generated by neighboring muscles should be less than 5% of the root mean square (RMS) amplitude from the muscle of interest during MVC. By determining when the surface EMG fell below this 5% threshold, we can theoretically estimate how close two surface EMG recording sites can be while remaining independent of each other. With no subcutaneous fat, the surface EMG fell below this 5% threshold 14 degrees away from the edge of the active muscle or approximately 1.0 cm from the active muscle’s edge. With a more typical fat layer of 9 mm, the surface EMG did not fall below this 5% threshold until 34 degrees, approximately 3.0 cm, from the active muscle’s edge.

Using the model it was shown that reducing the subcutaneous fat layer in a small region under the electrode can increase surface EMG amplitude and decrease cross-talk above neighboring muscles. Reducing the fat layer will bring the recording electrode closer to the active muscle, thereby increasing the EMG signal power and signal independence. Fat reduction procedures are routinely used for cosmetic reasons. If surface EMG signal power or cross-talk are problematic in a amputee (especially an obese patient), it seems reasonable to consider using these relatively simple surgical procedures for the functional purpose of improving the control of an artificial limb. There are several options for reducing the fat layer. Liposuction would be a simple method to reduce the fat layer, although it would not completely eliminate the fat layer.
Liposuction removal of the fat cells will cause a permanent decrease in the subcutaneous fat layer. However, if the patient continues to gain weight the remaining fat cells can hypertrophy, thus increasing the fat layer thickness (although it would still be thinner than the surrounding areas that were not reduced with liposuction). A more complete fat removal could be accomplished by surgically excising all of the subcutaneous fat in an opened procedure and laying the skin directly on to the muscle. With all of the fat cells gone, this would be a stable solution, albeit a more invasive procedure.

Procedures to enhance EMG signal independence (such as fat reduction) may also be useful to develop multifunction EMG controllers. For example, a pair of electrodes over the proximal forearm flexors and extensor is traditionally used to control the terminal device in a transradial prosthesis. However, the proximal forearm contains many different surface muscles that have different functions on the hand and wrist. Surgical procedures, such as fat reduction, that allow for more localized recording and greater signal independence from specific muscles may allow multifunction transradial myoelectric prostheses. If it were possible to record separate EMG signals from wrist flexors/extensors, wrist rotators and/or finger flexors/extensor, then simultaneous operation of a powered hand and wrist would be feasible, which would greatly improve the function of the transradial amputee.

Care must be taken when interpreting simulated data. Changing any of the parameters of the model will have an effect on the results. Some of the most important parameters to consider in the volume conductor model are the tissue conductivities and the muscle anisotropy ratio. We chose to use Gabriel’s (1996) parametric estimation of tissue conductivities and a muscle anisotropy ratio of 5, which lie in the middle of the range of reported values. However, the range of reported muscle anisotropy varies from 2.5-20. If an anisotropy ration of 2.5 were used the
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Falloff of the electric potential would be approximately 25-30% slower with a corresponding higher cross-talk. Similarly if an anisotropy ratio of 10 were used the falloff of the electric potential would be 25-30% faster with correspondingly lower cross-talk (Lowery et al., 2002a). Reducing the subcutaneous fat layer would still increase surface EMG signal amplitude and decrease cross-talk with these anisotropy values. If the ratio of muscle/fat conductivity were higher then the simulated surface EMG amplitude would be higher and cross-talk values would be lower (Andreassen and Rosenfalck, 1981; Lowery et al., 2002a). Conversely, a lower ratio of muscle/fat conductivity would result in lower surface EMG amplitudes and higher cross-talk values. For a further analysis of the effect of tissue properties on EMG signal propagation see Stoykov et al., 2002.

Conclusions

Finite element analysis indicates that subcutaneous fat significantly reduces surface EMG signal amplitude and increases EMG cross-talk at nearby surface recording sites. This may pose considerable problems in the control of myoelectric prosthesis. However, the results indicate that by reducing the fat layer in a small local area under the recording electrodes, surface EMG signal amplitude and signal independence may be increased.

Acknowledgements

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References


Figure Captions

Figure 1. Illustration of limb model cross-section and sample motor unit locations.

Figure 2. Finite element model of localized fat reduction in two areas 45° apart.

Figure 3. Simulated surface EMG interference pattern with a 3 mm subcutaneous fat layer.

Figure 4. RMS value of surface EMG signal at difference electrode locations around the limb.

The RMS amplitude of all EMG signals has been normalized with respect to the RMS value of the EMG signal detected directly above the center of the active muscle tissue in the model without subcutaneous fat tissue. Values are presented for 0 mm fat (solid line), 3 mm fat (dotted line), 9 mm fat (dashed line) and 18 mm fat (dot-dashed line).

Figure 5. Surface EMG cross-talk, defined as the ratio of the EMG RMS value at each electrode normalized with respect to the RMS value of the EMG signal detected directly above the center of the active muscle in that model. Values are presented for 0 mm fat (solid line), 3 mm fat (dotted line), 9 mm fat (dashed line) and 18 mm fat (dot-dashed line).

Table Captions

Table 1. Model Parameters.

Table 2. Effect of thinning a local region of subcutaneous fat from 9 mm to 3 mm. Single muscle fiber source is 3 mm below the surface of the muscle. Bipolar electrodes 20 mm apart.
Table 1.

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<th>Model parameter</th>
<th>Value</th>
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<tr>
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<td>10</td>
<td>Heymsfield et al., 1982</td>
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<td>Radius of muscle tissue (mm)</td>
<td>40</td>
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<td>Skin thickness (mm)</td>
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<td>0.2455</td>
<td>Gabriel et al., 1996</td>
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<td>Fat conductivity, $\sigma_f$ (S/m)</td>
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<td>5</td>
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<td>50</td>
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<td>Source length (mm)</td>
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<td>Muscle fibre length (mm)</td>
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<td>Mean motor unit firing rate (Hz)</td>
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<td>Inter-pulse-interval standard deviation, $SD$, about mean, $ipi$</td>
<td>$SD = 9.1x10^{-4}ipi^{1.4}$</td>
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<td>Simulated muscle fibre depths – distance below muscle surface (mm)</td>
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Table 2.

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<th>Uniform 3 mm fat layer</th>
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Figure 1
Figure 2
Figure 3
Figure 4
Figure 5