Dr. Pat Crago, Department of Biomedical Engineering  
Nathan Makowski, PhD Candidate in Neural Engineering  
Rakesh Guha, Bioelectricity Sequence

Electrical augmentation of muscle fibers for sufferers of paresis: controlling stimulation with voluntary signal

**Background**

A motor unit consists of a single motor neuron and a group of muscle fibers. A group of motor units that coordinate to control a muscle is called a motor unit pool. Motor units are innervated by a signal from the brain propagating the neuron, and triggering a muscle action potential at the neuromuscular junction. The motor unit action potential causes muscle fibers to contract, and the collective contraction of muscle fiber groups manifests as total muscle force.

Muscle activity can be measured on the skin surface as a potential difference across two electrodes. The resulting graph is called an electromyogram, and represents the time course of the sum of the MUAPs of a motor unit. The EMG can be rectified by taking the average of the absolute value, to obtain a relative quantification of the muscle activity.

**Model**

An experimental analysis of the EMG-Force relationship has generally resulted in a linear curve. Based on this relationship and known physiological properties of motor unit pools, a mathematical model of motor unit pools has been developed. Motor neurons generate an action potential at a threshold unique to each neuron. The distribution of thresholds in a pool of motor units is modeled by an exponential curve:

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where RR is the range of recruitment thresholds and n is the number of motor units in the pool. Similarly, amplitude of twitch force varies as:

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where RP is the range of twitch amplitude.

Contraction time is approximated as an inverse power function of the twitch force:

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where TL is the longest desired contraction time. In this representation, there are relatively few fast twitch motor units, and a large number of slow twitch motor units.

Motor unit firing rates increase linearly after recruitment, until reaching a peak firing rate related inversely to the recruitment threshold.

**Force model**

The force generated by a motor unit is nonlinearly related to the firing rate of the neuron. The percentage of maximum force over stimulus rate is a sigmoidal curve. In general, a greater stimulus rate yields a greater force.

**Pathology**

Force increases approximately linearly with rectified EMG in non-pathological muscles. Victims of stroke may suffer from muscle paresis, resulting in partial loss of movement in the limbs. The condition manifests as a reduced force output for a given EMG.

**Device**

To counteract this effect, electrical stimulation can be delivered to increase the force output of the muscle. Force is modulated in two ways. Increased force can be generated by recruiting more motor units, or increasing the firing rate of the recruited motor units. Both are achieved by an increased excitatory drive delivered to the motor neuron.

The amount of stimulation delivered should be proportional to the voluntary signal being transmitted from the neuron. This would allow users a greater degree of control over their motor function. For this to be possible, the device must be able to obtain the voluntary signal at any time.

However, the voluntary signal cannot be isolated from the stimulation signal. The surface EMG would instead be a combination of the MUAPs generated by the voluntary signal, those generated by the stimulation, and electrical artifacts caused by the stimulation electrodes interfering with the recording electrodes. Therefore, proper use of the device would require real-time filtration of the EMG to obtain an estimated voluntary EMG.

The scope of this project is to evaluate existing filtration techniques for this application. This is possible because of the mathematical model described above. The motor unit pool is modeled in MATLAB, and allows for excitation by both voluntary and electrical stimulation. Because the calculations are apparent, both the voluntary and combined signals are known. Filtering techniques can therefore be applied to the combined signal to obtain an estimated voluntary EMG. The result can be evaluated by comparison with the known voluntary EMG by residual analysis.

**Results**

**Development of the model**

Over the semester, the project involved adding the functionality of dynamic excitation to the model.

Previously, the model could only accept ‘static’ inputs of excitation, meaning that the excitation or stimulation level would have to remain constant over the course of the simulation. The approach for creating a model with dynamic input was fundamentally different than the original. With constant input, the firing frequency of each motor neuron is constant, and the firing times are determined at the onset.

Dynamic excitation means that the firing frequency is constantly changing, and the firing times must be determined based on the frequency at each time. To implement this, a ‘refractory period’ system was used. The firing frequency was calculated at every time point. Action potentials were suppressed if another action potential had fired before the time point, within one refractory period. The refractory period was calculated as the reciprocal of the firing frequency.

The results of the model were also formatted to implement three filters, coded in MATLAB as well.

**Evaluation**

The model can output a vector of the force over time and the EMG over time. Additionally, the EMG as generated by the stimulus pulses was also given. Subtracting this vector from the total EMG gives the volitional EMG alone.





The EMG vector can be broken up into frames that line up with the stimulus and input into the three different filter types. The filter will output a vector that approximates the value of the volitional EMG alone. Comparing this value to the actual volitional EMG can produce a value to evaluate the strength of a filter or filter configuration. The quantification was done by calculating the RMS of the residual of the two vectors.

**Rounding error**

The initial filter outputs gave an output that would occasionally ‘spike’ up, yielding a higher residual than expected, seen in the green line in the figure below.



It was eventually determined that the spikes were caused by a rounding error that was not visible even to three significant digits. When the rounding error was corrected, the spikes went away, as shown below.



**References**

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