THE EFFECTIVE ELECTRICAL ACTIVATION OF SKELETAL MUSCLE

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ABSTRACT: A new method of using distributed stimulation with optimised unequal interpulse intervals to stimulate skeletal muscle is described. Experiments carried out on cat skeletal muscles demonstrate that this method can be used to produce smooth contraction in fast muscle under conditions that more closely approximate physiological activation. This is important in studying human biomechanics as well as in fundamental muscle research. This research also demonstrates the possibility of using distributed stimulation for more effective activation and control in functional electrical stimulation (FES) of paralysed limbs.

INTRODUCTION

Returning function to limbs paralysed as a result of an accident or disease process has been a long sought after goal. Only in the last few decades, however, have technology and neuroscience advanced to the point where practicable systems can be built to partially realise this dream. Progress in replacing function through electrical stimulation has been more rapid in other biological systems, such as cardiacpacemakers and cochlear prostheses. Replacement of limb function has been slowed by the need to control substantial numbers of different muscles reliably and to provide sensors and sophisticated systems to adapt to the variety of environmental conditions we experience in normal motor activity. So in current FES application to paralysed limbs, all the fibres of a given muscle or muscle group are stimulated synchronously. This makes the muscles fatigue rapidly.

In contrast, natural muscle activation is characterised by thousands of motor units being asynchronously stimulated, so that individual twitches in different muscle fibres occur at different times, and the muscle mass has an integrating effect. This enables naturally activated muscle to develop smooth tension even at low stimulation rates by the action of statistical smoothing of many asynchronously activated small motor units, delay or prevent fatigue by involving only a portion of muscle’s motor units during a sustained contraction.

A method, which has been called “distributed stimulation”, was designed to approximate asynchronous activation [1]. This method involved dividing the muscle, via its nerve supply, into a number of portions that were then stimulated sequentially. Each of these portions, when stimulated, must produce a twitch of similar size. Distributed stimulation achieved smooth contractions with much lower stimulation rates compared to synchronous stimulation of the whole muscle or nerve. However this method needed near equal twitch tensions, which restricted its application to muscle dominated by slow type motor units. Most muscles have a mixture of fibre types, and fast fibres show much greater effects of stimulation history on tension, so that maintaining equal sized portions is almost impossible.

A method of multichannel distributed stimulation has been investigated in a computer model to test the new hypothesis that, if the muscle portions produce twitches of unequal amplitude, a smooth tetanus can still be generated by varying the interpulse intervals between stimulating the portions[2]. Building on this model, a novel algorithm is able to shift the interpulse intervals to minimise the tension ripple. Based on this model a portable and programmable eight channel muscle stimulator has been designed for distributed stimulation which uses unequal interpulse intervals to overcome unequal twitch amplitudes [3]. Experiments with fast and slow muscle preparation have demonstrated that this method can be used to produce smooth submaximal contraction at low stimulation rates for fast and slow muscle [4, 5].

DESCRIPTION OF THE RESEARCH CARRIED OUT IN MONASH UNIVERSITY C.B.E.

The first stage of this research was to build a computer model. The model has been implemented in Igor on Macintosh computers. A simple algorithm has been used for finding the optimal interpulse intervals. Simulations of fast and slow muscle showed that the problem of unequal twitch tensions can be very effectively reduced by using optimised unequal interpulse intervals, and that this approach can reduce the stimulation rate component of tension ripple to near zero.

Based on this model a microprocessor-based eight channel muscle stimulator has been designed and built. This muscle stimulator uses a microprocessor with interface devices to produce the stimulation pulses and acquire data, and uses a laptop computer to provide the user interface and to calculate the appropriate intervals. Some analog simulation results have demonstrated that this stimulator could be used in the physiological experiments.

Preliminary experiments have been conducted with cat soleus and medium gastrocnemius muscle. Anaesthesia was induced with an intraperitoneal injection of pentobarbital (40 mg/kg), and supplementary doses were given intravenously, when necessary, during the courses of experiments. Muscle was stimulated through ventral roots which were subdivided into six portions. Muscle lengths were changed and the isometric tensions were recorded. The results of the model were consistent with those of animal experiments. Experiments demonstrated that this method can be used to produce smooth submaximal contraction at low rates for fast and slow muscle.

IMPLICATION OF THIS METHOD IN MUSCLE MECHANICS
Much of the research on the mechanical properties of skeletal muscle has used maximal, synchronous stimulation to evoke smooth contractions. However, in the freely moving skeletal muscle the motor units are found to be activated submaximally and asynchronously [6]. So it is of considerable interest to have an understanding of the biomechanics of partially activated muscle. These measurements are difficult to make because at low rates of synchronous stimulation, muscles produce what is known as unfused contraction. Thus for example there have been few studies done for the force velocity relationship of moving skeletal muscle the motor units are found to be partially activated fast or mixed muscles. The mechanics of partially activated muscle is of significant relevance to the understanding of muscle function in normal usage, and in a control situation where the mechanical impedance of the mammalian skeletal muscle may need to be understood.

Figure 1 represents the active tension vs stimulation rate curve for cat soleus muscle with distributed stimulation. For some range of lower stimulus rates (5-15 pps), for which muscle is partially activated, the tension increases steeply with stimulation rate. From a mechanical perspective this slope will be relevant to mechanical function as it will, for example, affect mechanical stability.

The distributed stimulation developed in MUCBE therefore suggests the possibility of conducting a wide range of physiological studies on slow and fast muscle at different stimulation rates. Similarly it enables the behaviour of these muscles to be examined under conditions where the activation is changing in time. Thus it would appear that we can control muscle so that it either develops a desired level of tension, or establishes a desired level of mechanical impedance, by control of stimulation pulse rate, and use of distributed stimulation to deliver smooth tension at these low stimulation rates.

**IMPLICATION OF THIS METHOD IN FES**

In most FES applications to paralysed limbs, muscle is usually stimulated synchronously and tension is graded by varying the strength of the stimulation pulses. Stimulation rate modulation has only a limited range between acceptable fusion and maximum contraction, so that stimulation rates are usual high. The consequence is that the muscles nearest the electrodes are always recruited first, and so fatigue rapidly. Distributed stimulation of portions of a single muscle would help to reduce muscle fatigue, improve the control of muscle activation, and allow muscles to be partially activated. Distributed stimulation has not been applied in FES because of the difficulties of obtaining equal portions of muscle to independently control and keeping them equal if fatigue occurs more rapidly in some portions than others. The method proposed here needs information only on the fundamental ripple of tension, not the size of the portions. High frequency response and linearity of the tension transducer are not essential. This reduces the difficulties of applying this approach in an implanted FES application.

**CONCLUSION**

A method of distributed stimulation of skeletal muscle has been investigated in a computer model and in animal experiments. This approach uses unequal interpulse intervals between stimuli to minimise the effect of unequal sized twitches. Experimental results show that this method can be used in experiments to characterise the biomechanical behaviour of partially activated muscle as well as in FES. Fatigue and related instability of muscle can be reduced by contracting a greater portion of the muscle at lower stimulation rates to generate small to moderate tensions.

**REFERENCES**


