A Method to Effect Physiological Recruitment Order in Electrically Activated Muscle

Zi-Ping Fang and J. Thomas Mortimer

Abstract—**A new stimulation method has been utilized to achieve physiological recruitment order of small-to-large motor units in electrically activated muscles. The use of quasitrapezoidal-shaped pulses and a tripolar cuff electrode made selective activation of small motor axons possible, thus recruiting slow-twitch, fatigue-resistant muscle units before fast-twitch, fatigable units in a heterogeneous muscle. Isometric contraction force from the medial gastrocnemius muscle was measured in five cats. The physiological recruitment order was evidenced by larger twitch widths at lower force levels and smaller twitch widths at higher force levels in the muscles tested. In addition, force modulation process was more gradual and fused contractions were obtained at lower stimulation frequencies when the new stimulation method was employed. Furthermore, muscles activated by the new method were more fatigue-resistant under repetitive activation at low force levels. This stimulation method is simpler to implement and has fewer adverse effects on the neuromuscular system than previous blocking methods. Therefore, it may have applications in future functional neuromuscular stimulation systems.**

Introduction

Electrical stimulation may be used to restore lost motor function in paralyzed patients. However, conventional stimulation methods, using common electrode designs and stimulus waveforms, unavoidably excite larger motor units before smaller ones. This type of "reversed" recruitment order, as opposed to the physiological recruitment order during natural activation, results in poor force gradation and rapid muscle fatigue for electrically activated muscles [4]. Attempts have been made to reverse the recruitment order in electrically activated muscles by using either dc or high frequency blocking techniques [5], [6]. These methods require additional electrodes and stimulation channels, and may induce undesired neural activities at the onset of the block.

We have reported, in a companion paper, a new stimulation scheme for selective activation of small motor axons [2]. The scheme requires only one cuff electrode and one stimulus channel of transient current impulses. More importantly, this scheme permits immediate activation of small nerve fibers without any undesirable transient neural activity. The purpose of the work presented here was to demonstrate, through animal experiments, the feasibility of applying this unique stimulation technique to activate skeletal muscles in a natural, or physiological recruitment order. The expectation was that a well-graded and fatigue-resistant muscle contraction could be achieved with the new stimulation method. The preliminary results of this work have been reported elsewhere [3].

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Methods

Animal Preparation

Acute experiments were performed on five adult cats weighing 2.4–3.5 kg. The anesthesia and the installation of the spiral cuff electrode have been described in the companion paper [2]. Briefly, the animals were anesthetized with IM ketamine hydrochloride and then maintained on IV sodium pentobarbital. A spiral cuff electrode was placed on the medial gastrocnemius nerve. In addition, muscle force was recorded from the medial gastrocnemius during this series of experiments. Special caution was taken to preserve the blood supply to the muscle. The calcaneus was severed and attached to a stiff transducer for force measurement. The muscle length was adjusted to a length that produced a passive tension of about 1 N without force/length servo [1]. The nerve and muscle were bathed in lactated Ringer's solution at 37°C.

Twitch Contraction Test

A series of single quasitrapezoidal pulses [2] with varying current amplitude were applied to the cuff electrode to induce muscle twitch contraction and obtain the "descending" side of the force modulation curve in four animals. The twitch force profile corresponding to each stimulus strength was recorded with a chart recorder at a paper speed of 200 mm/s. Two indexes, "twitch force" and "twitch width," were used to characterize a twitch profile. Twitch force was defined as the peak amplitude of a muscle twitch after zeroing out the rest tension. Twitch width was defined as the time duration that was measured at a force level of 10% of the peak force in a twitch profile [4]. In one of the four animals, the entire test was repeated using 10 μs rectangular pulses to obtain the "ascending" side of the force modulation curve and the related twitch force and twitch width.

Tetanic Contraction Test

A cluster of 350 μs quasitrapezoidal pulses were delivered at a frequency of 20 Hz for a duration of 3 s for each stimulus current level in three animals. The current amplitude was adjusted so that tetanic forces decreasing at about 10% increments from 100 to 10% of the maximum tetanic force were obtained. A 12 s resting period was allowed between each two consecutive tetanic contractions. The entire test was repeated using 10 μs rectangular pulses in two of the three animals. An index of "ripple percentage" was used to quantify the degree of fusion during tetanic contraction. The ripple percentage was defined

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as the ratio of the peak-to-peak amplitude of the force fluctuation to the maximum amplitude of the entire force profile.

Fatigue Test

Two different protocols were employed to examine muscle fatigability. In one animal a continuous stimulation protocol was used. 20 Hz stimuli were applied continuously for 2 min in each test. In another animal, an intermittent stimulation protocol proposed by Burke was used [1]. 40 Hz stimuli were applied for a 330 ms burst in every 1 s, with each test lasting for about 5 min. Three tests were conducted in each animal. In the first and third test, the 10 μs rectangular pulses were applied. In the second test the 350 μs quasitrapezoidal pulses were applied. A 20 min recovery period was allowed between the tests. The current strength of either type of pulses was adjusted to an amplitude that induced a contraction of 5–10% of maximum force.

Results

Force Modulation by Differential Nerve Block

In electrical activation of skeletal muscles, muscle force is usually modulated by recruitment process, i.e., more motor units are recruited as stimulation strength increases. An example of this type of force modulation is shown in Fig. 1(a). A different type of force modulation process was tested in the present work. This force modulation scheme was based on a differential neural blocking process. As shown in Fig. 1(b), when the 350 μs quasitrapezoidal current pulses were applied through the tripolar cuff electrode, most of the alpha fibers were excited at a low pulse amplitude and a maximum muscle force was generated. However, when a higher amplitude pulse was applied some nerve fibers were differentially blocked, resulting in a lower muscle force. Furthermore, with an even higher amplitude pulse, all the alpha fibers were blocked, resulting in zero force.

In Fig. 2, the peak force of each twitch contraction in Fig. 1 is plotted as the function of stimulus current amplitude. The "ascending" and "descending" branch in the curve manifests the two different force modulation mechanisms: recruitment and "derecruitment," respectively. It is demonstrated that although force modulation can be implemented with either scheme, the slope of the descending side is more gradual than the ascending side. The force modulation characteristics with the differential block scheme were measured in four animals. The results were similar among the animals and 0–100% force range was demonstrated in every animal. These data are summarized in Fig. 3.

Twitch Width as an Indicator of Recruitment Order

Careful examination of the twitch profiles in Fig. 1 revealed that at lower force levels the twitches in Fig. 1(b) had longer durations than their counterparts in Fig. 1(a). To quantify this observation, the twitch width was measured for each twitch profile. The results for one animal are plotted in Fig. 4. The left side of the curve shows that the twitch width increased with increasing stimulus current when the narrow rectangular pulses were applied. This result indicates that the faster muscle units were recruited before the slower ones when the conventional stimulation scheme was used. The right side of the curve shows the relationship between stimulus amplitude and twitch width for the wide quasitrapezoidal pulses. In this case, the twitch width increased with higher current pulses. Because this curve

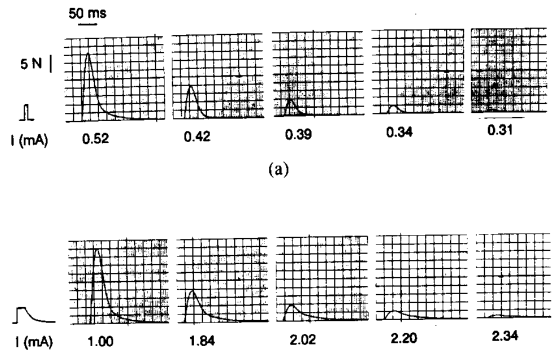

Fig. 1. Twitch force profiles. (a) With 10 μs rectangular current pulses, the peak force increased as the pulse amplitude increased. (b) With 350 μs quasitrapezoidal current pulses, the peak force decreased as the pulse amplitude increased.

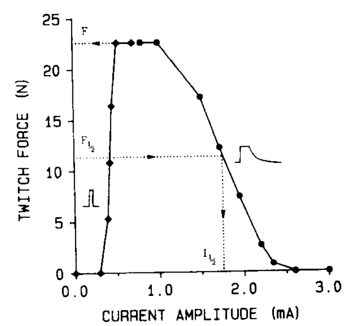

Fig. 2. Peak twitch force as a function of pulse amplitude with the two different stimulation schemes in the same animal. Data taken from Fig. 1. The twitch forces shown are the mean values of five successive twitches at each pulse amplitude. The standard deviations at each data point are less than 0.3 N.

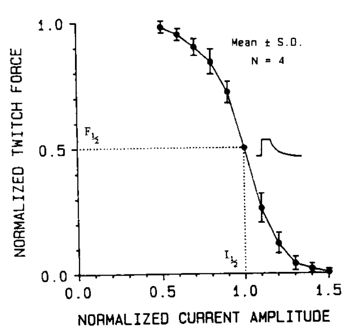

Fig. 3. Peak twitch force as a function of pulse amplitude with the 350 μs quasitrapezoidal pulses. Data from four animals are combined. The twitch forces were normalized to their maximum levels in each animal. The current amplitudes were normalized to the current value that induced a force of 50% of the maximum force in each animal (cf. Fig. 2).

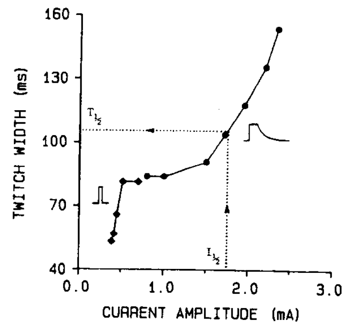

Fig. 4. Twitch width as a function of pulse amplitude with the two different stimulation schemes in the same animal. Data taken from Fig. 1. The twitch widths shown are the mean values of five successive twitches at each current strength. The standard deviations at each data point are less than 3 ms.

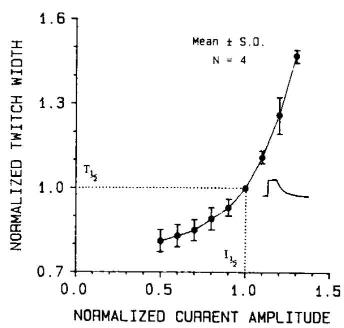

Fig. 5. Twitch width as a function of pulse amplitude with the 350 μs quasitrapezoidal pulses. Data from four animals are combined. The twitch forces were normalized to their values at 50% of maximum force levels in each animal. The current amplitudes were normalized to the current value that induced a force of 50% of the maximum force in each animal (cf. Figs. 2, 3, and 4).

corresponds to the descending side of the force modulation curve (cf. Fig. 2), the result of increasing twitch width at higher current levels indicates that the slow muscle units were activated at lower force levels. The data from all the four animals were consistent, i.e., the twitch width increased at higher stimulus current or lower force production levels. These data are presented in Fig. 5.

Tetanic Contraction Characteristics

Tetanic contractions are required for most practical applications of electrically activated muscles. Therefore tetanic contractions at different force levels were examined with the two types of stimulation schemes. A typical recording from one of the three animals tested is shown in Fig. 6. The ripple percentage at maximum force level was about 50% for both types of stimuli delivered at 20 Hz. Also, the ripple percentage was much smaller at low force levels with the new stimulation method than it was with the conventional method, as shown in Fig. 7. This is interpreted as being caused by the difference of recruitment order. The implication of this finding is that in order to produce a weak, but fused muscle contraction in a motor neural prosthesis, a lower stimulation frequency would be required with the new stimulation scheme. This would be beneficial in

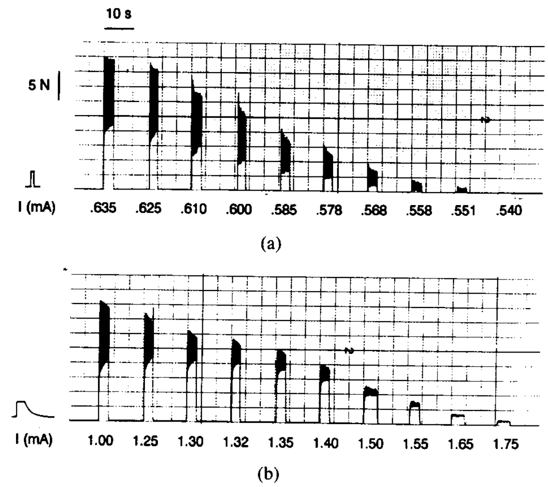

Fig. 6. Force profiles of tetanic contraction. (a) Tetanic contractions induced by the 10 μs quasitrapezoidal pulses. Note that the ripple percentage increased at lower force levels. (b) Tetanic contractions induced by the 350 μs rectangular pulses. Note that the ripple percentage decreased at lower force levels.

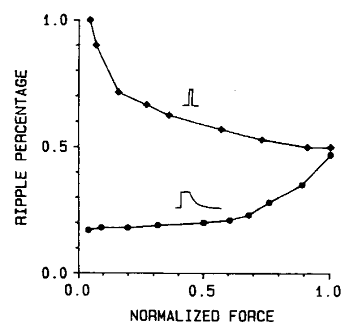

Fig. 7. Ripple percentage changes at different force levels with the two different stimulation schemes in the same animal. Data taken from Fig. 6.

reducing the muscle fatigue caused by high frequency stimulation imposed by the conventional method.

Muscle Fatigability with Preferential Slow Muscle Unit Activation

Muscle fatigue tests were performed in two preparations to demonstrate directly the improvement of muscle durability with preferential slow muscle unit activation. Fig. 8 shows the result from one animal where the continuous stimulation protocol was used. The force decay at the end of each test was 69% (first test) and 67% (third test) with the conventional stimulation scheme, and only 17% (second test) with the new stimulation scheme. Also, it can be seen again from these recordings that the ripple amplitude is smaller with the new stimulation method. Fig. 9 shows the result from a second animal where the intermittent stimulation protocol was used. The force decay at the end of each test was 72% (first test) and 38% (third test) with the conventional scheme, and only 16% (second test) with the new scheme. These results suggest that muscles are more fa-

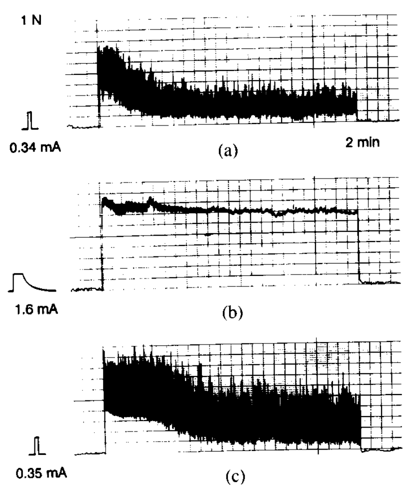

Fig. 8. Muscle fatigability during continuous activation of two minutes. (a) First test. With the 10 μs rectangular pulses, the force decay was 69% at the end; (b) Second test. With the 350 μs quasitrapezoidal pulses, the force decay was 17% at the end; (c) Third test. With the 10 μs rectangular pulses, the force decay was 67% at the end. The axis scales are same in all the recordings. A 20 min recovery period was allowed between the tests.

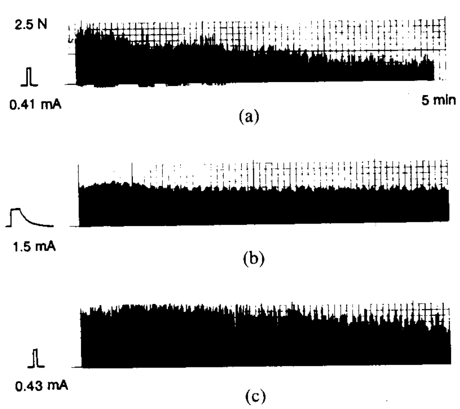

Fig. 9. Muscle fatigability during intermittent activation of 5 min. (a) First test with the 10 μs rectangular pulses, the force decay was 72% at the end; (b) second test with the 350 μs quasitrapezoidal pulses, the force decay was 16% at the end; (c) third test with the 10 μs rectangular pulses, the force decay was 38% at the end. The axis scales are same in all the recordings. A 20 min recovery period was allowed between the tests.

tigue resistant, at low force production levels, when they are driven by the new stimulation method.

Discussion

In this work, a stimulation technique for selective activation of small fibers was used to achieve physiological recruitment order in skeletal muscles. Muscle twitch and tetanic contractions were characterized by indexes such as twitch width and ripple percentage to compare the recruitment order elicited by conventional and new stimulation scheme. Fatigue tests were conducted to show directly the influence of recruitment order on muscle durability during repetitive activation.

The possibility of controlling motor unit recruitment by differential block of larger nerve fibers has been explored by other investigators. Graded direct voltage was applied through a second pair of electrodes distal to the stimulation site to effect differential block [5]. However, direct current causes tissue damage so that this method can not be used for clinical purposes. High frequency stimulation has also been used in addition to the regular stimuli to obtain physiological recruitment order [6]. According to the authors, this scheme works by the mechanism of neurotransmitter or calcium depletion rather than brief block of nerve conduction [7]. There are also some undesirable neuromuscular activities at the onset of the high-frequency stimulation. In contrast, the stimulation technique presented in this paper requires only one type of stimulus and a single channel electrode. It works by transient membrane hyperpolarization and can drive the neuromuscular system to any desired status instantly.

In the present work, the index "twitch width" was used instead of more commonly used parameters such as "twitch contraction time" and "half-relaxation time" in characterizing twitch profiles. This is because when stimulation is applied to a nerve trunk (rather than a single neuron) to activate a heterogeneous muscle such as medial gastrocnemius (rather than a homogeneous muscle such as soleus) "twitch contraction time" and "half-relaxation time" of a "compound twitch" profile could be easily biased by a few strong, fast motor units, even though there are more weak, slow motor units involved. By using "twitch width" which takes the duration of the bottom part (at 10% force level of the peak force) of a "compound twitch" the contribution from slow motor units can be reflected even when some fast motor units are simultaneously activated.

In the fatigue tests shown in Figs. 8 and 9, a third trail with rectangular stimuli was conducted to validate that the difference between first and second run was not due to the activation history of the muscle, but rather the stimulation scheme itself. The muscle appeared more fatigue-resistant in third trial than it was in first trial though same stimulation scheme was employed. The reason for this paradox is that some of the fastest, most-fatigable motor units were fatigued out during the first trial so that to attain same initial force the amplitude of the stimuli had to be increased to recruit some less-fast motor units which were not involved in the first trial and those motor units are usually less fatigable than the ones which they replaced. It should be noted that the order in which these tests were run was deliberate to account for this phenomenon.

It is also seen that the force profiles in Figs. 8 and 9 exhibited certain degree of fluctuation. This is probably due to the fact that these force traces were obtained with submaximum stimulation strength inducing a force of only 5–10% of maximum force of the muscle, in contrast to conventional supramaximum stimulation which causes a more stable force output. It is likely that some motor units with an activation threshold very close to the stimulus amplitude setting could respond to a particular stimulus but not the next one of same amplitude because of the transient change of threshold during repetitive stimulation. However, it can be seen that the force induced by the new stimulation scheme is more stable than those by the conventional scheme. This difference could be attributed to the fact that many weak, slow motor units had to be activated to generate a low force output in a muscle when the new scheme was used, while much fewer strong, fast motor units were excited to produce the same level of force when conventional schemes were used. Thus, if one motor unit added in or dropped out due to threshold variation, the consequent force change should be much less with the new scheme.

In conclusion, the effectiveness of the proposed technique in generating physiological recruitment order has been demonstrated. The results indicated that slow-twitch, fatigue-resistant muscle units in a heterogeneous muscle could be activated before fast-twitch, fatigable units by the new stimulation method. Force modulation by "derecruitment" was more gradual and easier to control, and muscle contraction activated by the new stimulation scheme was more fatigue-resistant. In light of these findings, the stimulation method tested in this work may have applications in future motor prostheses.

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