

Recruitment Patterns in Human Skeletal Muscle During Electrical Stimulation

Electromyostimulation (EMS) incorporates the use of electrical current to activate skeletal muscle and facilitate contraction. It is commonly used in clinical settings to mimic voluntary contractions and enhance the rehabilitation of human skeletal muscles. Although the beneficial effects of EMS are widely accepted, discrepancies concerning the specific responses to EMS versus voluntary actions exist. The unique effects of EMS have been attributed to several mechanisms, most notably a reversal of the recruitment pattern typically associated with voluntary muscle activation. This perspective outlines the authors' contention that electrical stimulation recruits motor units in a non-selective, spatially fixed, and temporally synchronous pattern. Furthermore, it synthesizes the evidence that supports the contention that this recruitment pattern contributes to increased muscle fatigue when compared with voluntary actions. The authors believe the majority of evidence suggests that EMS-induced motor unit recruitment is non-selective and that muscle fibers are recruited without obvious sequencing related to fiber types. [Gregory CM, Bickel CS. Recruitment patterns in human skeletal muscle during electrical stimulation. *Phys Ther*. 2005;85:358–364.]

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Electromyostimulation (EMS) incorporates the use of electrical current to activate skeletal muscle and facilitate contraction. It is commonly used in clinical settings to mimic voluntary contractions and enhance the rehabilitation of human skeletal muscles. Although EMS is a commonly accepted modality in the management of conditions that include skeletal muscle dysfunction, the mechanisms associated with its effects are not widely agreed upon and, in many cases, are misunderstood. One such misunderstanding revolves around muscle fiber recruitment patterns during EMS-induced contractions. Thus, the purpose of this communication is to present an evidence-based perspective that muscle fiber recruitment during EMS is in a nonselective, spatially fixed, and temporally synchronous pattern rather than in a reversal of the physiological voluntary recruitment order.

The ability of electrical stimulation protocols to improve skeletal muscle performance in healthy and dysfunctional muscle is widely accepted and routinely demonstrated in research studies as well as in clinical practice.¹⁻⁷ However, although most investigators report increases in muscle performance with its use, there are discrepancies in the literature concerning the specific responses to EMS versus voluntary actions. Interestingly, the unique effects of EMS training have been attributed to several mechanisms, most notably a reversal of the recruitment pattern that is typically associated with voluntary muscle activation.⁸ The Henneman size principle of voluntary motor unit recruitment describes the progressive recruitment of small, typically slow, motor units followed in order of increasing size to the larger, typically fast, motor units (Fig. 1).⁹ The suggestion that the use of EMS results in a reversal of the size principle, therefore recruiting larger (fast) motor units prior to the slow, is based on 2 commonly agreed upon findings: (1) the axons of the larger motor units have a lower resistance to current and conduct action potentials at faster rates than the axons of the smaller motor units, and (2) data demonstrate increased fatigue with EMS versus voluntary activation. The data used to support a reversal of recruitment order will be re-examined in this perspective.

Physiological Data

Data from neurophysiological studies^{10,11} demonstrate that the axons of larger motor units are more easily depolarized and that there is a positive relationship between axonal size and conduction velocity. It is generally accepted that these larger axons are associated with large motor units that typically innervate the fast, more fatigable fibers. These findings imply the potential for preferential fast fiber recruitment with artificial electrical activation. However, Kim et al¹² concluded that, although this neurophysiological phenomenon may hold true for direct stimulation of the motor nerve in vitro or in situ, orientation of the peripheral nerves may not favor the activation of these fibers with cutaneous electrical stimulation, thus resulting in a more random pattern of recruitment during EMS. In another study, Feiereisen et al¹³ measured recruitment thresholds of 302 motor units from the tibialis anterior (TA) muscle during voluntary and EMS-induced contractions at various intensities. These authors demonstrated that, in 94% of the cases, the size principle held true during voluntary contractions, whereas 28% to 35% of the trials using EMS resulted in a preferential recruitment of the fast motor units. Thus, they concluded that there is commonly (~30% of trials) a reversal of the size principle using EMS-evoked contractions. If a true reversal took place, we would expect it to occur in more than 30% of the trials. These data cast doubt on the principle of a reversal of motor unit recruitment according to size, as the majority of the trials (~70%) in the TA muscle did not demonstrate this pattern. Interestingly, the TA muscle in humans is composed of ~30% fast fibers,¹⁴ leading us to conclude that the magnitude of “preferential recruitment” found in the study by Feiereisen et al was more likely due to a nonselective recruitment pattern, indicative of the inherent properties of this particularly “slow” muscle. Thus, our interpretation of these data suggests that a reversal of the size principle is not a phenomenon associated with EMS.

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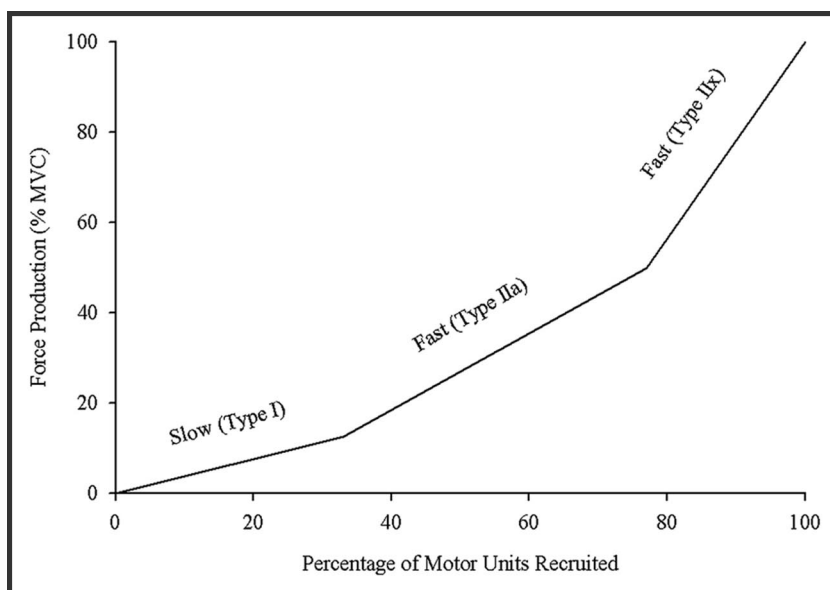


Figure 1.

Graphic representation of the orderly recruitment of motor units during voluntary activation of skeletal muscle as described by Henneman et al.⁹ Slow (type I), Fast (type IIa), and Fast (type IIb) motor units are represented. MVC= maximal voluntary contraction.

Additional support for the aforementioned nonselective recruitment pattern produced by EMS is provided by Knaflitz et al.¹⁵ This study showed that both mean and median frequency as well as conduction velocity increased with increasing force during EMS-induced contractions. Interestingly, these patterns were similar to those found during voluntary recruitment of the TA muscle.¹⁵ The finding that both frequency and conduction velocity increase in proportion to fast motor unit recruitment suggests that EMS does not result in a reversal of the normal recruitment pattern. Thus, the authors concluded that “contrary to what is observed in direct stimulation of nerves, motor units are not, in general, recruited in reverse order of size during electrical stimulation of a muscle motor point. This discrepancy may be the result of geometric factors or a lack of correlation between axonal branch diameter and the diameter of the parent motoneuron axon.”^{15(p1657)} This conclusion supports our contention that the resulting recruitment order during EMS-induced contractions is nonselective.

It is important to recognize that responses to EMS evoked using surface electrodes, as used clinically, are different than responses to EMS produced by direct stimulation of motor nerves and result in a different physiological environment relative to the *in vitro* or *in situ* animal designs. Previous studies,^{16,17} as well as some commonly used textbooks,^{18,19} presume the reversal of recruitment pattern based on studies of lower mammals. However, factors that affect current flow, and therefore muscle activation *in vivo* (ie, skin impedance, subcuta-

neous fat, peripheral nerve orientation, and so on), result in a different physiological environment relative to the animal studies. Thus, although the neurophysiological principles commonly used to support a reversal of recruitment order are based on well-designed studies, these principles do not strictly apply during typical EMS applications to humans.

The increase in fatigue during EMS is another commonly cited finding used to support the reversal in recruitment order. In most studies examining the influence of EMS on fatigue, subjects are either electrically stimulated to evoke a given force or asked to voluntarily produce a force equal to a specific percentage of their maximal voluntary contraction (MVC). In the EMS trial, the stimulator is left on with the parameters (ie, frequency and amplitude) remaining constant for a given length of time. In the voluntary trial, the same subjects are asked to attempt to maintain the

given force over the same time period. Force measures are continually monitored during both sessions. The relative drop in force between the 2 different activation methods is compared, and fatigue is consistently greater during the EMS trial. This increased fatigability with EMS is thought by some researchers to suggest a reversal of the size principle of recruitment, thus the recruitment of primarily fast, fatigable fibers at relatively low force levels. However, another plausible explanation would be that, during voluntary actions, alternate recruitment patterns allow for recruitment of additional motor units when fibers that were initially recruited become fatigued. Electromyostimulation does not permit alterations in recruitment of motor units. In addition, during voluntary actions, muscle force also can be maintained by modulating the firing rates of active motor units.²⁰ Thus, the ability to counter fatigue (ie, maintain external force production) in voluntary efforts can be accomplished by one or both of the following: (1) recruiting different motor units as those initially recruited become fatigued (ie, alternate recruitment patterns) or (2) activating additional motor units at lower firing frequencies.

Interestingly, some investigators do consider fatigue to be occurring when additional motor units are recruited, even though no measurable drop in force is realized. This example was illustrated by Carpentier et al,²⁰ who measured electromyographic (EMG) activity of the first dorsal interosseus muscle during repeated contractions. Even though a submaximal force output could be maintained, this was accomplished by recruiting additional motor units, as evidenced by increased EMG activity.

This recruitment strategy is not available during EMS-induced muscle contractions. Recruitment of muscle fibers with EMS is fixed and results in a subsequent drop in force whenever any of the fibers activated during the protocol become fatigued. This is one of the fundamental problems of using EMS for functional activities. We suggest that the greater fatigue that occurs with EMS-induced contractions is associated with the inability to alter recruitment patterns or the inability to modulate firing frequency, or both, and is not due to preferential recruitment of fast, fatigable fibers.

Consideration should be given to the fact that, in addition to functional limitations, fixed recruitment of motor units may not be advantageous from a metabolic perspective. The nondiscriminant activation of fast and slow motor units during relatively low levels of work at firing frequencies that are higher than those typically achieved would result in an exponential increase in energy demand to accomplish a given task. For example, needle EMG has been utilized to measure the frequency of activation of human skeletal muscles during voluntary activation. Slow and fast skeletal muscles have been shown to have firing frequencies of approximately 10 and 30 Hz, respectively, during MVCs.²¹ These frequencies are lower than those typically applied during EMS. Often, clinicians use frequencies of 50 Hz or more to ensure tetanic contractions. Thus, the frequency of EMS contractions also may contribute to fatigability.

Metabolic Data

A study that is often referenced to infer preferential recruitment of fast versus slow fibers during EMS was published by Sinacore et al.¹⁶ In this study, the vastus lateralis muscle of a single subject was biopsied before and immediately after EMS-induced muscle activation. The biopsies were analyzed for histochemical determination of glycogen content. The authors performed a visual analysis of the fiber optical density, which is indicative of glycogen content. Their analysis suggested greater depletion of glycogen stores in the fast fibers versus the slow fibers. This finding was interpreted to suggest preferential recruitment of fast versus slow fibers during EMS-induced muscle activation. However, assuming the qualitative analysis was correct, it is interesting to note that the total glycogen content, as measured quantitatively, was not different in pre-versus post-stimulation samples. Nevertheless, in defense of these results, the fact that glycogen utilization is greater in fast versus slow fibers is not surprising given that fast fibers have a higher energy demand for contraction than slow fibers as well as an increased glycogen phosphorylase activity.^{22,23}

Application of the aforementioned explanation of fixed recruitment during EMS would allow for the increased glycogenolysis to be explained by metabolic factors

rather than by recruitment patterns. The metabolic characteristics of individual fibers are reported to be responsible for the greater relative glycogen depletion in fast versus slow fibers during high-intensity voluntary exercise.²⁴ During high-intensity voluntary exercise where recruitment is near maximal, both fast and slow fibers are activated. We propose that the metabolic demand during maximal exercise is similar to that placed on fibers activated during EMS at high frequencies, and thus the results should be interpreted similarly.

A complete analysis of glycogen utilization during electrical stimulation and voluntary exercise was conducted by Kim et al.¹² In this study, skeletal muscle biopsies were taken from the vastus lateralis muscle before and after knee extension exercise evoked by either voluntary or EMS contractions. Work rate remained constant at about 30 W in both conditions. Both voluntary and EMS-evoked contractions resulted in significant glycogen depletion, with the vastus lateralis muscle showing greater glycogen depletion after EMS contractions than after voluntary exercise. A more specific look at patterns of glycogen depletion in skeletal muscle fiber types showed that all fiber types after EMS actions had significant reductions in glycogen, and there did not appear to be preferential recruitment of any fiber subtype.

Mechanical Data

Data concerning the mechanical properties of muscle also suggest that there is not a reversal in recruitment patterns using EMS. For example, in a study using a competitive weight lifter by Delitto et al,¹⁷ fiber size changes resulting from EMS training showed an average reduction in cross-sectional area of the fast fibers and an increase in size of the slow fibers. Although a reduction in fiber size of either type is surprising, preferential activation of the fast fibers likely did not occur. If it did, we might expect selective hypertrophy of those fibers.

Binder-Macleod and colleagues²⁵ investigated the twitch and force-frequency relationship of the quadriceps femoris muscle at different stimulation intensities. They reported that the twitch contractile speeds were not different when the muscle was stimulated at intensities that evoked 20%, 50%, or 80% of MVC.²⁵ We might predict faster twitch times at 20% of MVC when compared with 80% of MVC, assuming a reversal in recruitment order. This was not the case in this study, and the data lend support for a nonselective pattern of activation when utilizing surface electrical stimulation to activate muscle. Further endorsement of this nonselective activation pattern is provided by the fact that the study also showed no difference in the force-frequency relationship when it was investigated at 20% and 50% of MVC.²⁵

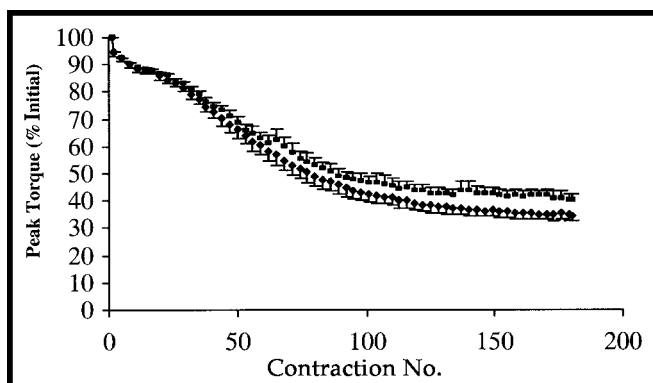


Figure 2.

Peak torque of quadriceps femoris muscle during a 180-contraction (six 200-microsecond square-wave pulses, 70-millisecond interpulse interval) fatigue protocol under 2 different conditions (moderate- and high-amplitude conditions started at either 25% or 50% of maximal voluntary contraction, respectively). Peak torque was reduced by about 60% under moderate- and high-amplitude conditions. Figure reprinted with permission from: Slade JM, Bickel CS, Warren GL, Dudley GA. Variable-frequency trains enhance torque independent of stimulation amplitude. *Acta Physiol Scand.* 2003;177:87-92.

In a recent study by Slade et al,²⁶ fatigue tests were performed on subjects with different stimulation intensities. If it is assumed that there is preferential activation of fast fibers early on with EMS, it would seem logical that relative fatigue would decrease as stimulation intensity is increased. This would be based on the fact that the more fatigue-resistant slow fibers would be recruited only at the higher relative intensities. However, as stimulation intensity was increased, fatigue did not change (Fig. 2), thus lending additional support to refute a preferential recruitment of fast fibers and supporting the idea of nonselective, fixed recruitment. In addition, the rate of rise from 20% to 80% of stimulated peak torque did not differ during stimulation intensities that differed by 2-fold. This finding further supports our contention of a nonselective pattern of activation with EMS. If the recruitment pattern using EMS recruits motor units in a fast-to-slow manner, we would expect the rate of rise in torque to decrease with increasing intensities due to the increased number of slow fibers being recruited. However, given the similarities in rise time, the more reasonable explanation is derived from the nonselective, random recruitment pattern we have previously described.

Bickel et al²⁷ investigated the fatigability of the quadriceps femoris muscle (predominantly fast fibers) and the TA muscle (predominantly slow fibers) in human skeletal muscle. This study utilized relatively low force levels, and the authors contend that it was highly unlikely that any more than 50% of the available muscle was activated. Accordingly, if a preferential recruitment of fast motor units did occur, we would have predicted similar rise

times. This would be based on the fact that predominantly fast fibers would have been recruited at these intensities. However, the data indicate that the TA muscle had significantly slower rise times than the quadriceps femoris muscle, owing to its predominantly slow phenotype, and provide further mechanical data to support a nonselective pattern of activation.

Additional Data

Magnetic resonance imaging (MRI) is a common, although relatively new, technology utilized to measure muscle activation. It has been determined to be a valid and reliable method of quantifying the amount of muscle used during both voluntary and electrically stimulated activities.²⁸ Adams et al²⁹ were the first investigators to map the pattern of activation after EMS-evoked isometric contractions of the quadriceps femoris muscle. Two interesting points were made based on these data. The first point that the authors made was that EMS contractions, even at low levels of force, can recruit muscle fibers deep within the muscle, even those next to the femur. It has generally been accepted that EMS activates the most superficial nerves and therefore cannot activate fibers deep within a large muscle group such as the quadriceps femoris muscle. However, although the motor nerves might be superficial, the fibers innervated by these nerves are seemingly spread throughout the muscle. This finding provides additional evidence of nonselective recruitment using EMS. The second point that Adams et al²⁹ made was that the reversal of motor unit recruitment theory can be explained by the relationship between activated muscle cross-sectional area and external torque generation. This relationship has repeatedly been shown to be linear in nature.²⁹⁻³¹ In addition, active muscle as determined from MRI is reported to predict 74% to 92% of the variance in torque from EMS actions.^{29,31} The linear relationship reported is of significance because it is generally accepted that large, fast motor units produce more torque because the fast fibers are typically larger and the fast motor unit contains a greater number of fibers, when compared with slow motor units. If there was a reversal in recruitment pattern, resulting in fast-to-slow activation, we might expect a curvilinear relationship instead of the linear relationship that is reported (Fig. 3).

Discussion

This article has outlined numerous studies that support our contention that electrical stimulation recruits motor units in a nonselective, spatially fixed, and temporally synchronous pattern. Furthermore, this article synthesizes the evidence that supports the contention that this recruitment pattern contributes to increased muscle fatigue when compared with voluntary actions. The nonspecific pattern of activation seen with EMS is con-

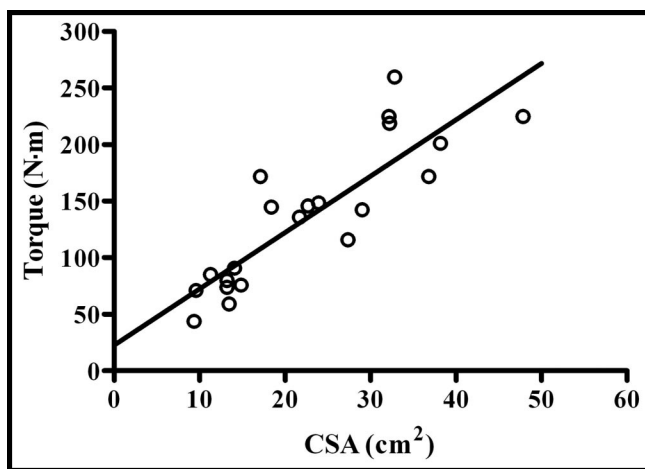


Figure 3.

The relationship between electrically stimulated cross-sectional area (CSA) and torque of the quadriceps femoris muscle during isometric actions ($R^2=.74$). Figure reprinted with permission from: Adams GR, Harris RT, Woodard D, Dudley GA. Mapping of electrical muscle stimulation using MRI. *J Appl Physiol.* 1993;74:532–537.

trary to what many people understand to be occurring, which is a reversal of the size principle and a resultant preferential recruitment of fast fibers during EMS-induced contractions. We assert that both slow and fast fibers are nonselectively activated with EMS at low or high force levels.

It is important to note that nonselective recruitment can provide clinical advantages in that all fibers, regardless of type, have the potential to be activated at relatively low intensities. A good example is provided in the treatment of muscle atrophy after periods of disuse (eg, immobilization, joint arthroplasty). The ability to activate fast fibers that would not typically be recruited during normal daily activities in this patient population might be beneficial. The therapeutic effect of artificially activating these fibers should help attenuate the responses to disuse and accelerate recovery. This may be the mechanism that is primarily responsible for many of the gains in performance demonstrated using EMS training protocols.

In conclusion, the idea that EMS-induced contractions result in a reversal in the normal recruitment pattern, and thus preferentially recruit fast versus slow motor units, has been suggested for many years. We contend, however, that the literature supports a nonselective, synchronous recruitment pattern of muscle fibers occurs with EMS. We acknowledge that EMS can be used to activate fast motor units at relatively low force levels, and this activation may be beneficial in the clinical setting and potentially thought of as preferential activation. However, we believe the majority of evidence suggests that EMS-induced motor unit recruitment is nonselective

and muscle fibers are recruited without obvious sequencing related to fiber types.

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