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# Neural adaptation to resistance training

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## ABSTRACT

SALE, D. G. Neural adaptation to resistance training. *Med. Sci. Sports Exerc.*, Vol. 20, No. 5 (Supplement), pp. S135–S145, 1988. Strength performance depends not only on the quantity and quality of the involved muscles, but also upon the ability of the nervous system to appropriately activate the muscles. Strength training may cause adaptive changes within the nervous system that allow a trainee to more fully activate prime movers in specific movements and to better coordinate the activation of all relevant muscles, thereby effecting a greater net force in the intended direction of movement. The evidence indicating neural adaptation is reviewed. Electromyographic studies have provided the most direct evidence. They have shown that increases in peak force and rate of force development are associated with increased activation of prime mover muscles. Possible reflex adaptations related to high stretch loads in jumping and rapid reciprocal movements have also been revealed. Other studies, including those that demonstrate the "cross-training" effect and specificity of training, provide further evidence of neural adaptation. The possible mechanisms of neural adaptation are discussed in relation to motor unit recruitment and firing patterns. The relative roles of neural and muscular adaptation in short- and long-term strength training are evaluated.

STRENGTH TRAINING, NEURAL ADAPTATION, MOTOR UNIT ACTIVATION

In response to resistance (strength) training, changes within skeletal muscle are an important and perhaps the major adaptation. However, voluntary strength performance is determined not only by the quantity and quality of the involved muscle mass, but also by the extent to which the muscle mass has been activated. Further, the expression of voluntary strength may be likened to a skilled act, in which prime movers must be fully activated, and synergists and antagonists appropriately activated. It is possible that strength training causes changes within the nervous system that allow a trainee to more fully activate prime movers in specific movements and to better coordinate the activation of all relevant muscles, thereby effecting a greater net force in the intended direction of movement. Changes within the nervous system may also allow force to be developed more rapidly and peak force to be maintained longer. The training-induced changes within the nervous system will be referred to as neural adaptation. The evidence indicating neural adaptation to strength training will be reviewed first, after which possible mechanisms of neural adaptation will be considered. Neural adaptation to strength training has been the subject of other recent reviews (58,85,86).

## EVIDENCE OF NEURAL ADAPTATION

### Electromyographic Studies

Electromyographic studies have provided the most direct assessment of neural adaptation to training. These studies have primarily focussed on changes in motor unit activation in prime movers following training.

**I EMG.** The most common electromyographic method in these studies has been to record, by surface electrodes, the motor unit activity in primer mover muscles during brief, isometric contractions done before and after strength training. The recorded motor unit activation is quantified as the integrated electromyogram (I EMG). I EMG has increased after strength training involving weight lifting (39–41,75), isometric contractions (60), "isokinetic" (constant velocity) eccentric contractions (59), and "explosive" jumping (42). In two studies, correlations were tested for and found between the increases in voluntary strength and the increases in I EMG (40,42). These findings are interpreted as indicating that strength-trained subjects can more fully activate prime mover muscles in maximal voluntary contractions.

One study that showed an increase in I EMG after weight training is illustrated in Figure 1 (75). In the trained arm, the increase in strength was associated with both an increase in I EMG and an increase in muscle size. Strength also increased in the contralateral untrained arm but was associated only with an increase in I EMG, indicating that the "cross-training" effect was the result of neural adaptation. When hypertrophy of muscle fibers does occur with training, the motor unit activation (number of active units and their firing rates) required to produce a given force decreases (Figure 1).

A study (98) which failed to show an increase in I EMG after weight training demonstrates the specificity of movement pattern and contraction type in strength

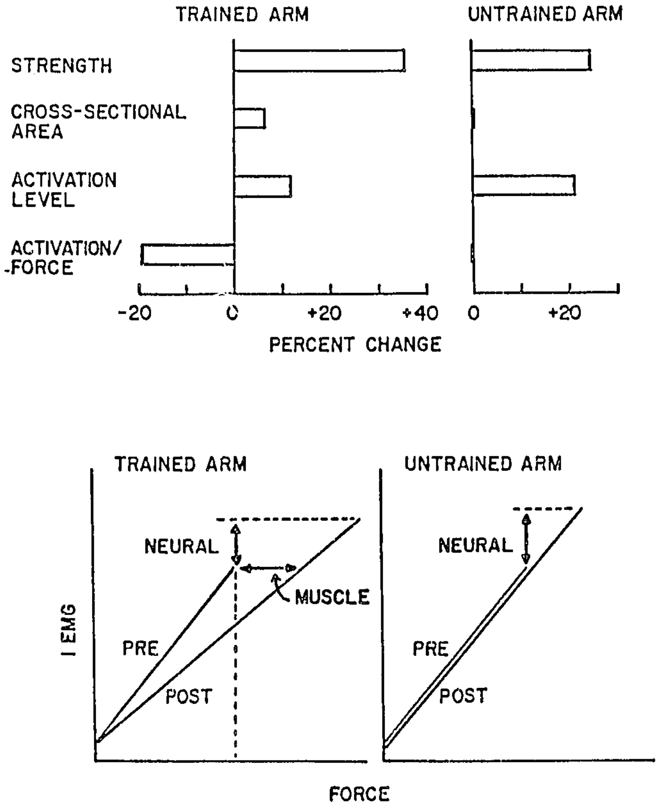

**Figure 1—Effect of weight training of the elbow flexors on strength, muscle size, and motor unit activation, the latter indicated by I EMG. *Top left*: Increased strength in the trained arm was associated with an increase in both muscle size and activation level (I EMG). The motor unit activation required to produce a given force decreased, presumably because of hypertrophy of muscle fibers of the active units. *Top right*: Voluntary strength also increased in the contralateral untrained arm ("cross-training" effect) but was only associated with increased I EMG. There was no change in activation/force ratio. *Bottom left*: Interpretation of changes in the relation between I EMG and voluntary muscle force. In the trained arm, peak force and peak I EMG increased, the latter being evidence of neural adaptation. The I EMG/force relation was shifted to the right, indicating that a smaller number of hypertrophied motor units could produce a given force after training. *Bottom right*: In the untrained arm, the increased force was only associated with increased peak I EMG, indicating that neural adaptation was solely responsible for the cross-training effect. Based on (75).**

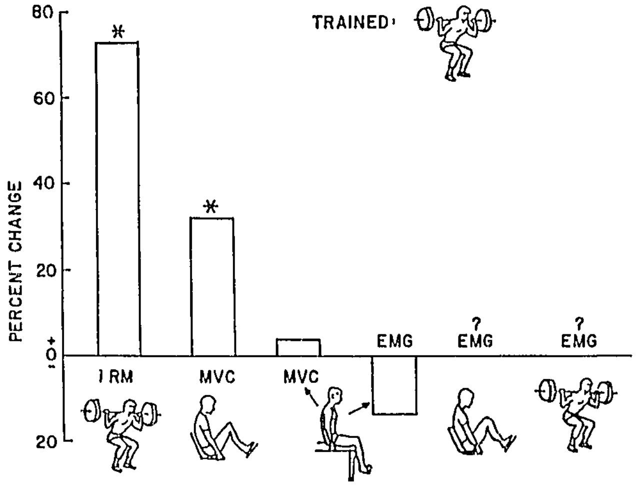

**Figure 2—Effect of weight training on various measures of voluntary strength and I EMG. Eight weeks of barbell squat training caused a large increase in specific weight lifting strength (1 RM = one repetition maximum), a smaller though significant increase in isometric leg press strength (MVC = maximal voluntary contraction), but no increase in isolated isometric knee extension strength. It was in this latter movement that I EMG was measured, and, like the MVC, there was no significant change. I EMG (EMG?) was not measured in the movements in which voluntary strength increased. These results emphasize the specificity of strength training. Based on (97).**

training (Figure 2). Training with the barbell squat exercise caused a large increase in weight lifting strength, a significant though smaller increase in an isometric leg press movement, but no increase in isometric knee extension strength. It was in this last movement that I EMG was measured pre- and post-training, and no change occurred. If EMG had been recorded in the two movements in which strength increased, perhaps an increase in EMG would have been observed.

Increased motor unit activation, as reflected by an increase in I EMG, may not only increase the peak force that can be developed, but may also increase the rate of force development. Specific training may be required, however. Thus, heavy resistance weight training caused primarily an increase in isometric peak force, associated with increased I EMG late in the EMG recording (41). In contrast, "explosive" jump training caused primarily an increase in isometric rate of force development and an increase in EMG at the onset of the EMG recording (42). The different changes in the EMG response to the two types of training may reflect a neural component to the observed specificity of velocity in strength training (Figure 3).

EMG has also revealed a possible neural adaptation to high stretch loads, as in jumping or "plyometric" exercise. In jumping down to the floor from a height of 110 cm (drop jumps), an untrained subject responded with a period of inhibition (reduced EMG) during the eccentric contraction phase after landing (stretch load), whereas a trained jumper responded with a period of facilitation during the eccentric phase (Figure 4; 58). The facilitation found in the trained jumper may be an adaptation of certain reflex responses. The adaptation may be specific to particular stretch loads. For example, male volleyball players are particularly superior to untrained men in doing drop jumps from a specific height (57), which may impose a stretch load most similar to that encountered when playing volleyball.

A final example of this approach to EMG relates to a possible coordination or reflex adaptation. In sprinters and distance runners, knee flexor EMG was monitored during rapid alternate knee extension and flexion on an isokinetic dynamometer. During the extension phase when the flexors were acting as antagonists, relatively greater flexor activity was observed in the sprinters (Figure 5; 78).

**Reflex potentiation.** A second electromyographic technique that has been used to monitor changes in

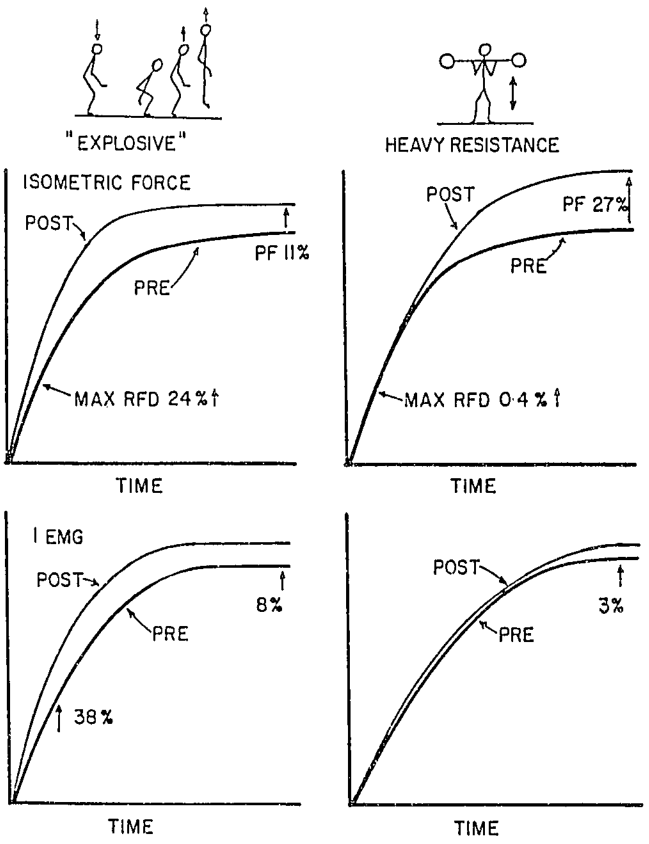

Figure 3—Comparative effects of "explosive" jump training and heavy resistance weight training on the force-time and EMG-time characteristics of isometric contractions of the knee extensors. Explosive training caused a relatively greater increase in maximum rate of force development (MAX RFD) than peak force (PF) (*top left*), whereas heavy weight training caused a large increase in peak force but little change in MAX RFD (*top right*). In the EMG-time curves, explosive training caused increases primarily at the onset of motor unit activation (*bottom left*), while weight training caused only a small increase in EMG later in the activation period. Based on (41,42).

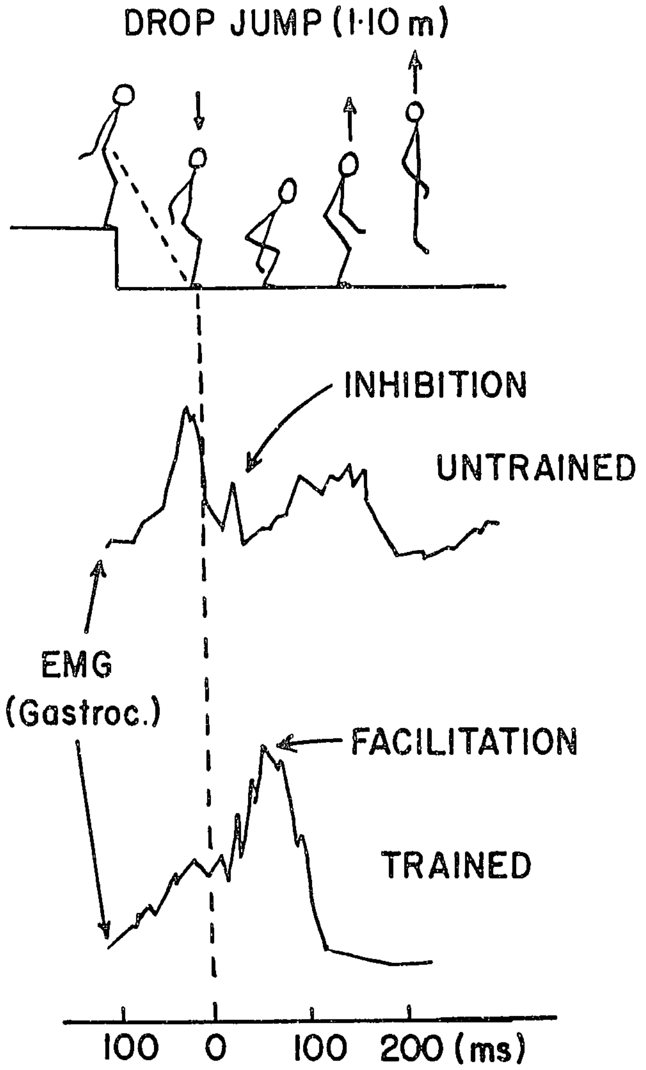

Figure 4—EMG recordings from the gastrocnemius muscle during drop jumps in an untrained subject (*top*) and in a trained jumper (*bottom*). During the eccentric phase of high stretch load (to immediate right of vertical dashed line at time 0), the untrained subject responded with a period of inhibition. In contrast, the trained jumper responded with a period of facilitation. The facilitation in the jumper may reflect a neural adaptation to training that is related to reflex responses. Based on (58).

motor unit activation has been to measure the degree to which certain reflex EMG responses are potentiated by maximal voluntary contractions (100). In this method, responses to supramaximal nerve stimulation at rest and during voluntary contractions are compared, and "potentiation ratios" can be calculated. Strength training, consisting of weight lifting and isometric exercise, caused an increase in reflex potentiation in some (88) but not all (87) muscle groups investigated (Figure 6). Cross-sectional studies have shown reflex potentiation to be enhanced in weight lifters (73,89) and in elite sprinters (Figure 7) (101). With this method, it is assumed that the degree of reflex potentiation is correlated with the degree of motor unit activation achieved by voluntary effort.

**Synchronization.** A third electromyographic method that has been used to observe the effects of training has been to determine the degree of synchronization of discharge of motor units during voluntary contractions. A longitudinal strength training study showed an increase in motor unit synchronization, and a cross-sectional study showed enhanced motor unit synchronization in weight lifters and in others who regularly perform brief, maximal contractions (Figure 8; 73). Unlike the first two electromyographic methods discussed, in which it is easy to conceive how an increase in the values obtained could increase the force of voluntary contraction, it is not readily apparent how an increase in motor unit synchronization could increase the force of voluntary contractions. On the contrary, at submaximal firing frequencies, force output is greater with asynchronous motor unit activation, and, at firing frequencies similar to the maximum observed in voluntary contractions, there is no difference in force attained between synchronous and asynchronous discharge (66,81). If synchronization of motor units can-

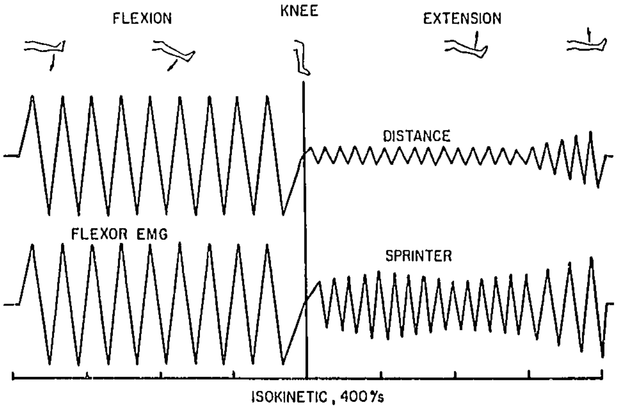

**Figure 5—Schematic representation of knee flexor EMG during alternate rapid knee extension and flexion on an isokinetic dynamometer. In the extension phase, when the flexors were acting as antagonists, flexor activity was greater in sprinters than distance runners. The difference in flexor activity may reflect specific neural adaptation to training. Based on (78).**

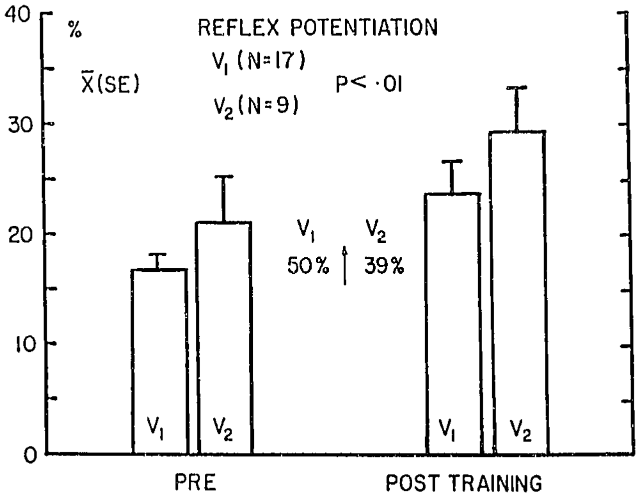

**Figure 6—Effect of strength training on reflex potentiation. Weight training and isometric training of several muscle groups caused an increase in the potentiation, by voluntary effort, of two reflex responses evoked by nerve stimulation. $V_1$ and $V_2$ refer to first and second volitional waves, respectively. For more details, see (88).**

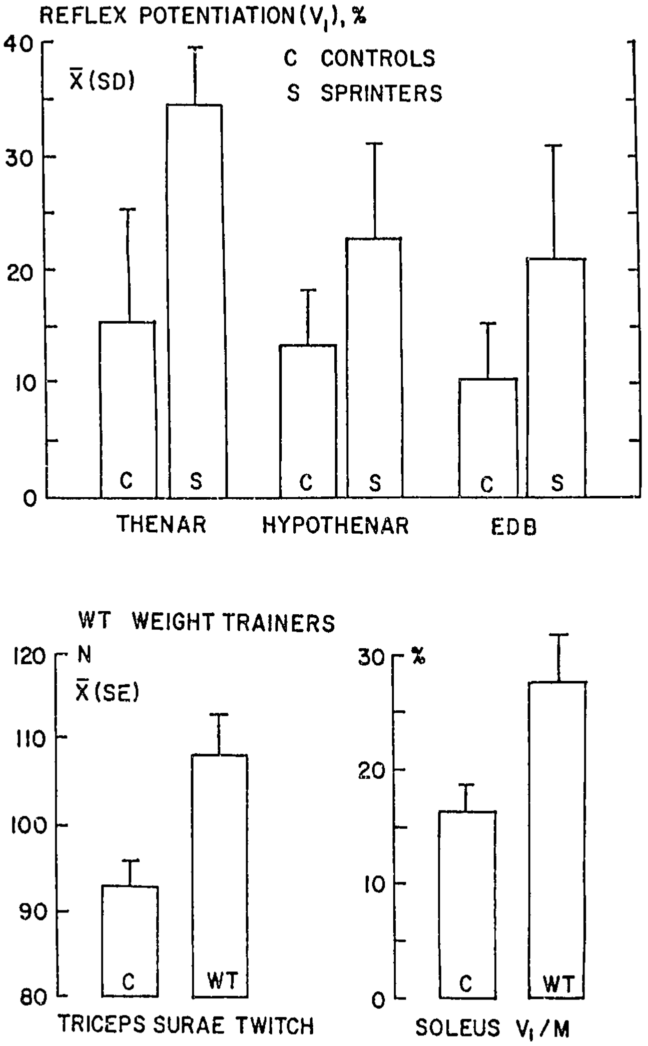

**Figure 7—Reflex potentiation in athletes. *Top*: Reflex potentiation was greater in elite sprinters than control subjects in small muscles of the hand and foot. As these muscles are not prime movers in sprinting, the results may express a particular genetic endowment of the sprinters. Based on (101). *Bottom*: Trained weight lifters had a greater soleus reflex potentiation and evoked triceps surae peak twitch force than control subjects. These results could reflect a combination of genetic endowment and the effects of training. Based on (89).**

not increase the peak force of voluntary contractions, perhaps it could increase the rate of force development of brief, maximal contractions. However, in experiments in which maximal voluntary contractions of the first dorsal interosseus were compared to evoked tetanic contractions at frequencies as high as 200 Hz, greater rate of force development was observed in the voluntary contractions (71). Therefore, the role of increased synchronization in enhancing strength performance remains unclear.

**Recordings from single motor units.** Few studies have assessed changes in motor unit recruitment and firing rates after training on the basis of recordings from single motor units. In fatigue studies with the short toe extensors (37), some subjects were unable to fire high threshold units at rates necessary for complete fusion. After repeated experiments, these subjects were then able to achieve higher firing rates; at this point their voluntary force matched the force evoked by tetanic stimulation. The repeated experiments, which consisted of sustaining maximal contractions, were a form of strength training. This training also increased the time (from a few to about 20 s) that the highest threshold motor units could be kept active in sustained maximal contractions (Figure 9) (37).

Training allows both low and high threshold units to maintain regular (less variable) firing intervals (less fluctuation in firing rate from spike to spike) at lower rates than before training (56). This change might be interpreted as increasing the range of firing rates over which motor units can maintain tonic (as opposed to phasic or intermittent) firing. Perhaps this adaptation

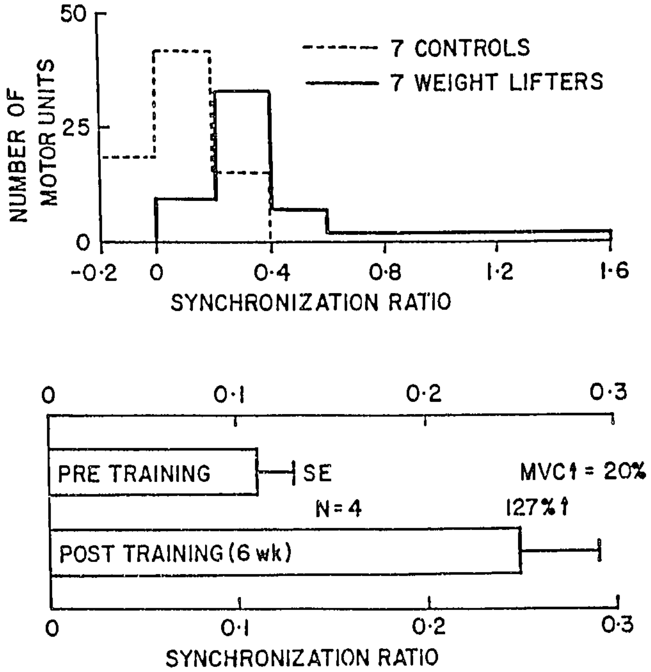

**Figure 8—Effect of strength training on motor unit synchronization. *Top*: Synchronization of discharge of motor units was greater in weight lifters than untrained control subjects in a small muscle of the hand. *Bottom*: A period of high resistance strength training of a small hand muscle caused a significant increase in motor unit synchronization. Based on (73).**

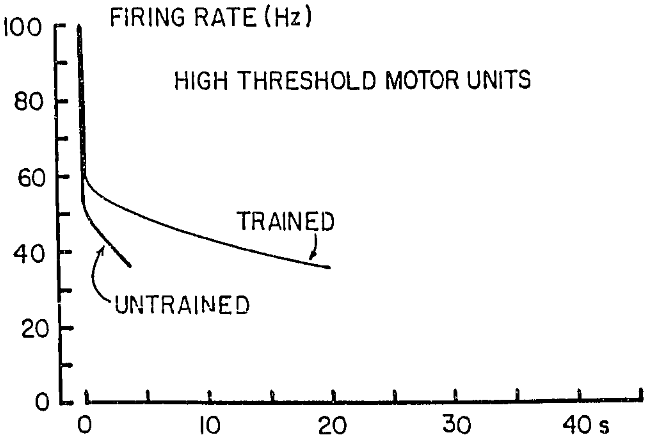

**Figure 9—Firing pattern of high threshold motor units of the short toe extensor muscle during sustained maximal voluntary contractions. At the onset of the contraction, the motor units discharged briefly (about 100 ms) at a high frequency (about twice the rate needed to produce maximum force; see also Figure 10). Thereafter the firing rate declined rapidly. Untrained subjects could not keep the highest threshold motor units active for longer than a few seconds. In contrast, trained subjects kept the highest threshold units active for about 20 s. Subjects trained by repeating the experiment several times over a period of weeks. Based on (37).**

allows higher threshold units to fire continuously longer before they fire intermittently or cease to fire altogether. In a related study, isometric strength training resulted in an increased ability of subjects to discharge motor units at regular firing intervals (fewer lapses in firing), whereas high repetition dynamic training resulted in a trend toward reduced ability to maintain regular firing intervals (17).

### Other Studies

Evidence in addition to that obtained from electromyographic studies indicates that adaptive changes occur within the nervous system in response to strength training. The evidence (reviewed in more detail in 85) includes: a) training-induced increases in voluntary strength without increases in evoked (by electrical stimulation) twitch and tetanic tension (18,69); b) training-induced increases in voluntary strength with little or no hypertrophy (15,29,60,75,82,96,97); c) the "cross-training" effect, in which training of one limb causes increases in strength in the contralateral untrained limb (47,52,60,75,107) without hypertrophy (47,52,62,75) or increases in evoked contraction strength (30); and d) specificity of training, in which increases in voluntary strength are specific to the movement pattern (40,84,97), joint position (6,35,67), contraction type (e.g., isometric vs dynamic) (29,53,59,67,97), and velocity (12,16,40,53,54,74,82) used in training. In these studies neural adaptation is inferred on the basis that little or no adaptive changes could be detected within muscles after training. Qualitative changes in muscle cannot be excluded entirely, however. For example, isometric vs ballistic concentric contraction training have been associated with specific changes in evoked contractile properties of human muscles (30).

## POSSIBLE MECHANISMS OF NEURAL ADAPTATION

The mechanisms of neural adaptation may include increased activation of prime movers in a specific movement, and appropriate changes in the activation of synergists and antagonists. The latter mechanism would be expressed as improved skill and coordination (84). The two mechanisms may contribute in different proportions in training with different movements.

Most of the EMG studies reviewed above were devoted to the first mechanism—increased activation of prime movers—whereas both mechanisms could be implicated in the other studies indicating neural adaptation.

### Extent of Motor Unit Activation

If increased activation of prime movers is an important and common adaptation to training, there is the implication that many untrained people cannot fully activate motor units in prime movers during maximal voluntary contractions. Insufficient motivation or some form of inhibition prevent full activation under normal conditions. Evidence bearing on this implication will now be reviewed.

**Two methods of assessing motor unit activation.** Two methods have been used to assess the extent of motor unit activation during maximal voluntary contractions. In the first, the force of a voluntary contraction is compared with the force produced by maximal tetanic stimulation (7,8,28,32,37,51,70). In the second method, called the interpolated twitch technique, a single supramaximal stimulus is applied to the nerve of the muscle engaged in a maximal voluntary contraction. If all motor units have not been fully activated, the stimulus will cause an increment to appear on the voluntary force recording (4,5,14,20,64,70). Both methods have been applied in several muscles in unilateral, single joint, isometric contractions. The number of subjects tested is relatively small. Nevertheless, many untrained but well motivated subjects can fully activate their muscles, as assessed by these methods. There is, however, considerable intersubject variability in the ability to fully activate muscles, and some muscles are more difficult to activate than others. For technical reasons, the methods cannot be applied to the large muscle group, bilateral, multijoint movements often used in strength training and performance. It is possible that a larger proportion of untrained people would have difficulty achieving full motor unit activation in these more complex movements.

**Motor unit firing rates.** An indirect way of determining whether full motor unit activation has occurred is to compare observed firing rates of motor units during maximum voluntary contractions to those rates expected to be needed to produce maximum tetanic contractions of the motor units. In the short toe extensors and tibialis anterior, the observed maximum firing rates of 30 Hz and 60 Hz for low and high threshold motor units would be sufficient for maximum force development, based on motor unit and whole muscle twitch contraction times (31). In contrast, high threshold (and presumably fast twitch) motor units in deltoid had lower maximum firing rates than low threshold units; it was suggested that the unexpectedly low firing rates in the fast high threshold units were insufficient for maximum force development and were the result of insufficient voluntary drive (excitatory input) on the motoneurons (19).

**Hypnosis and sensory stimuli.** For people who cannot achieve full motor unit activation under normal conditions, hypnosis and special sensory stimuli (e.g., derived from shouting) may permit greater activation. It has been proposed that some form of inhibition limits performance, but in unusual circumstances disinhibition can occur (50).

**Unilateral vs bilateral contractions.** Is is more difficult to achieve full motor unit activation in bilateral (both limbs acting simultaneously) than unilateral contractions in some movements. Thus, the force produced in bilateral contractions is less than the sum of forces produced by the right and left limbs contracting singly (16,45,49,76,77,102–104). The reduced force in the bilateral condition is associated with a reduction in the integrated EMG in prime mover muscles (49,77,102). The bilateral deficit is greater in some movements than others (103) and may be absent (61) in others. In one experiment, bilateral performance was actually superior to summed unilateral performance (106, cited in 2, p. 108).

The mechanism responsible for the bilateral deficit is not known, although various possibilities have been discussed (77,91,102) and challenged (49). Other features of this phenomenon are of interest. First, the bilateral deficit is present, in both force and EMG, in both isometric and rapid ballistic dynamic contractions (102), suggesting that the mechanism acts at higher centers involved in programming the movement in addition to any reflex effects. Indeed, in one movement tested, the bilateral deficit was not present in isometric and low velocity concentric contractions. The deficit only occurred at high concentric contraction velocities (103). Second, the bilateral deficit is minimized or abolished when contraction of a muscle group in one limb is simultaneous with contraction of the antagonists of the contralateral limb (77). Third, training with bilateral contractions reduces the bilateral deficit, as indicated after periods of training (16,83) and by observations made on athletes who train with bilateral contractions (same direction with both limbs) (49,90).

**Co-contraction of antagonists.** Contraction of agonists (prime movers in a task) may be associated with simultaneous contraction of their antagonists, particularly when the agonist contraction is strong and rapid (34,93), when the task requires precision, or when subjects are untrained in the task (79). The co-contraction of antagonists may provide stabilization during rapid and precise agonist contractions (3), and act as a braking mechanism in ballistic contractions (13,65,68). However, contraction of antagonists also impairs, by reciprocal inhibition, the ability to fully activate the agonists, as indicated by reduced I EMG (99) and motor unit firing rates (38). It has been suggested that this inhibition is a protective mechanism in activities (e.g., weight lifting) involving very strong co-contractions (99). Thus, when subjects are introduced to a new and relatively complicated strength task, excessive co-contractions of antagonists may limit full motor unit activation in agonists. Practice and training may reduce the amount of co-contraction, thereby allowing greater activation in agonists and a greater net force in the intended direction of movement (3). On the other hand, it may be advantageous to have considerable antagonist activity during rapid alternating movements. In rapid alternating knee extension and flexion, sprinters had greater antagonistic flexor activity during the extension phase than distance runners (78).

**Which motor units are difficult to fully activate?.** If many untrained people cannot fully activate prime mover muscles in maximal voluntary contractions, which motor units are the most difficult to activate? In voluntary contractions of increasing strength, motor units are generally recruited in order according to their size; that is, the largest and strongest (and fastest twitching) units are the last to be recruited and raised to the firing rate necessary for peak force development. Units of this type with the very highest thresholds are probably the ones that untrained people cannot fully activate. (For a detailed discussion of the "size" principle of motor unit recruitment, see the following reviews: 11,33,44,86.)

The relative roles of recruitment and variation in motor unit firing rate in grading the force of contraction of a muscle may affect the ease with which the muscle can be fully activated. In small hand muscles (19,63,72) most if not all motor units are recruited by about 50% MVC; thereafter, increases in force are brought about by increased firing rates of already recruited units. Untrained people should have no difficulty in recruiting all units in these muscles; it may be difficult to raise the firing rate of all units to that required for maximum force. In other muscles, such as biceps (63), brachialis (55), deltoid (19), soleus (5), tibialis anterior (43), and extensor digitorum brevis (36), motor units are recruited throughout the range of contraction force. Untrained people may have difficulty in both recruiting and obtaining optimal firing rates in the highest threshold units in muscles like these.

Untrained people may also have difficulty in keeping the highest threshold motor units active in sustained maximal voluntary contractions. In fatigue experiments with the short toe extensors, untrained individuals were able to keep the highest threshold motor units active for only a few seconds, whereas trained individuals could keep these units active for about 20 s (37; also see Figure 9).

**Peak force vs rate of force development.** In brief maximal contractions motor units will briefly fire at rates much higher than those needed for maximum force development (23,27). Thus, motor units may fire at 100 Hz for about 100 ms at the onset of a contraction, although maximum force is attained at a frequency of 50 Hz. The very high firing rate will, however, increase the rate of force development, based on stimulation experiments (37) (Figure 10). The highest firing rates occur during maximal "ballistic" contractions, in which subjects attempt to contract as quickly as possible (23). Repeated attempts at contracting rapidly (i.e., "explosive" training) may increase the ability to fire motor units briefly at very high rates. Rate of force development would therefore increase even if peak (isometric) force did not increase. This adaptation might account for the specific effects of "explosive" training upon rate of force development and the time course of the EMG (Figure 3). It would also contribute to the observed specificity of velocity in training.

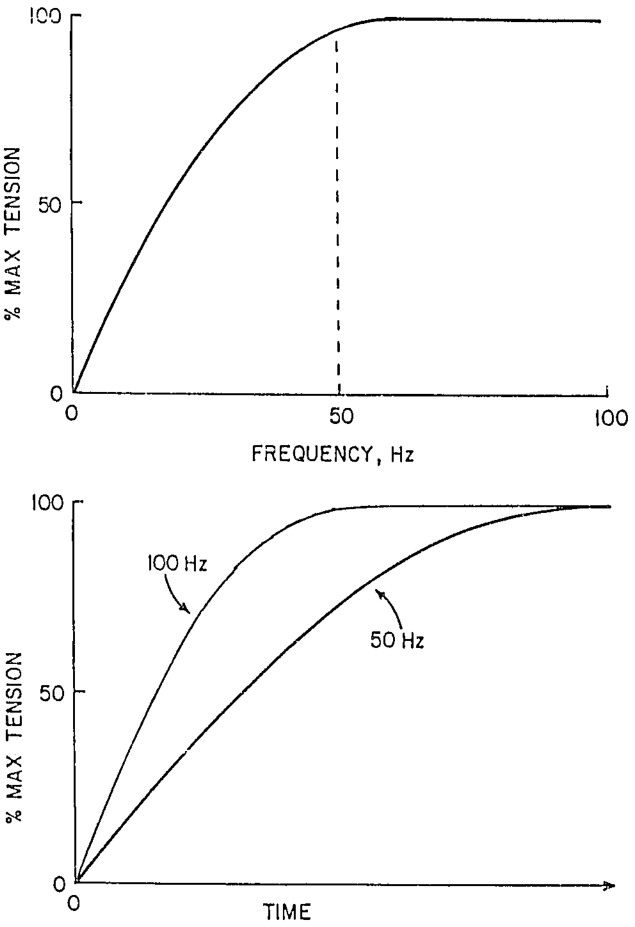

**Figure 10**—***Top***: **A stimulation frequency of 50 Hz is sufficient to produce maximum tetanic tension of the short toe extensor muscle. Higher frequency stimulation did not increase peak force further.** ***Bottom***: **High frequency stimulation will, however, increase the rate of force development. Thus, the usefulness of the high motor unit firing rates seen at the onset of voluntary contractions is revealed (e.g., Figure 9). Strength training that emphasizes contracting as rapidly as possible may increase the maximum motor unit firing rates, thereby increasing rate of force development. Based on (37).**

Specificity of velocity in training also raises the issue of whether there is preferential or exclusive activation of high threshold fast twitch motor units in ballistic contractions; such contractions occur in many sport movements and related training exercises. There is some evidence from human and more from animal research indicating synaptic input systems that are biased to excite fast twitch and inhibit slow twitch motor units (reviewed in detail in 11,86; for example of recent evidence, see 1). However, most studies which have compared recruitment patterns in slow "ramp" versus "ballistic" contractions have not shown reversals of recruitment order or selective recruitment of fast twitch units (10,22–27) in humans. Two exceptions are experiments in which rapid "twitch" contractions in certain conditions were associated with exclusive recruitment of normally high threshold units. In other rapid contractions, the firing patterns of units indicated biased net excitation in favor of high threshold motor units (36,43). Because of technical limitations, large muscles involved in activities such as kicking, jumping, and throwing have not been studied in humans. Therefore, no conclusion can be made at present as to whether selective or preferential recruitment of fast twitch motor units occurs in "explosive" sport performance and training.

**Specificity of movement pattern.** The recruitment order of some motor units in multifunctional muscles is task dependent; furthermore, some motor units may be preferentially recruited for specific tasks. This behavior has been observed in both small (21,27) and large (80,94,95,105) multifunctional muscles in humans. Related studies with animals have led to the suggestion that there may be task-specific groups of motor units within multifunctional muscles (46).

The relative activity of muscles within a functional group may also be task specific (9,48,92). For example, muscles acting at the elbow joint are most active when the movement corresponds to the muscle's greatest mechanical advantage (9). The relative activity of elbow flexors is influenced by the position of the forearm (2, p. 109).

The task-specific activation of motor units within a muscle and among synergistic muscles may be part of the basis for the observed specificity of movement pattern in strength training.

## NEURAL VS MUSCULAR ADAPTATION

Strength training studies typically involve training programs that last 8–20 wk. In these studies the early increases in voluntary strength are associated mainly with neural adaptation such as improved coordination or learning (84) and increased activation of prime mover muscles (39,75). In contrast, serious athletes train over a period of many months or years (Figure 11). Whereas the short-term experiments emphasize the importance of neural adaptation, progress at the intermediate and advanced stages of training may be limited to the extent of adaptations within muscles (e.g., hypertrophy). This would explain the avid interest in anabolic steroids among advanced strength trainers. It might be argued that specificity of movement pattern is not crucial in advanced training, because any training exercise that induces hypertrophy of the appropriate muscles would be effective. However, it would be most efficient to induce hypertrophy only in the muscle fibers of motor units that are activated in the sport movement. Hypertrophy of irrelevant muscles and motor units might even be counterproductive, particularly in sports which require a high strength to body mass ratio. Certain qualitative adaptations within muscle fibers (e.g., contractile speed) may depend upon the pattern of activation by motoneurons (e.g., high frequency bursts of impulses as in ballistic contractions). Therefore, it is probably important to pay attention to the nervous system and specificity even in advanced strength training.

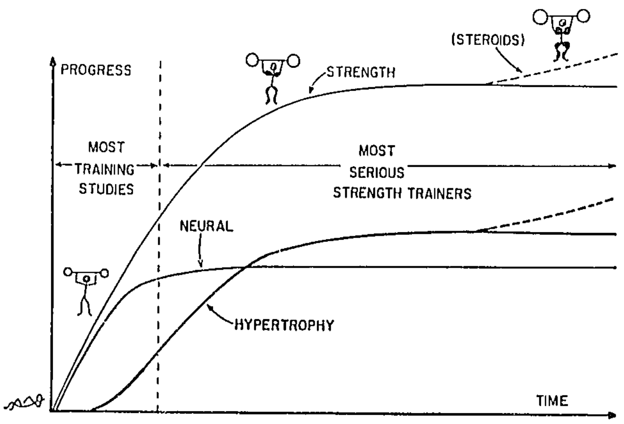

**Figure 11—The relative roles of neural and muscular adaptation to strength training. In the early phase of training neural adaptation predominates. This phase also encompasses most training studies. In intermediate and advanced training, progress is limited to the extent of muscular adaptation that can be achieved, notably hypertrophy—hence the temptation to use anabolic steroids when it becomes difficult to induce hypertrophy by training alone. See text for further discussion.**

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