The Ultimate Scientific Guide to Neural Adaptations to Exercise: A Practical Approach

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Journal of HYPERPLASIA Research 7(1):

Published February 7th, 2007

INTRODUCTION

In a recent lecture I gave to the exercise physiology students here at Florida State University I opened up by explaining that one of the typical responses we are all familiar with in terms of enhanced strength are the increases in muscle tissue growth that are seen. The rationale is quite intuitive: A greater amount of contractile tissue equates to a greater capacity to perform activities which require high force outputs such as weight lifting. However, I followed up with the statement that individuals are actually able to gain strength without gaining muscle tissue. The question is "How?" A while passed after asking this question, until a bright student raised his hand and said "I got it!" The nervous system adapts." He was correct. In the following paper I intend to outline a fairly complex subject, in what I feel is a very understandable format. A format which will attempt to answer a number of the most popular questions including:

"Should athletes train limbs separately, such as in the one legged squat or leg press?"

"Can athletes learn to inhibit many of the body's protective mechanisms which naturally suppress strength in a given activity?"

"Why is it that during rare occasions ordinary people are able to perform seemingly superhuman feats of strength, such as when a Mom lifts a car off of her child? Is this neurological, and can I train myself to perform this way in the gym?"

"How does the body call into play muscle fibers to perform a certain exercise, and how can I increase / optimize this "recruitment process?"

"How do neural adaptations differ between strength and endurance activities, and do they conflict with each other?"

This is but a sampling of what will be discussed in the following paper, in which the purpose is to allow you to realize how the body adapts to training neurologically, and how in turn these changes will ultimately affect both muscle tissue growth, and overall athletic performance. Special care is taken to provide the reader with practical applications for each adaptation discussed.

BASIC NERVOUS SYSTEM OVERVIEW

How movement is initiated

It has been said that the brain is the most complex structure in the universe. For ages scientists have been stifled by its extreme and elaborate network of interconnecting cells which process information at speeds which befell our most advanced computing systems. What is interesting however is that evidence actually suggests that as you descend down to the spinal cord that the system very well may become more complex.

The first concept to be aware of is where movement begins. This is in the cortex or the 'wrinkly' part of the brain. At the side of this region is an aspect of the brain known as the motor cortex where specialized neural cells called upper motor neurons arise (Fig. 1).

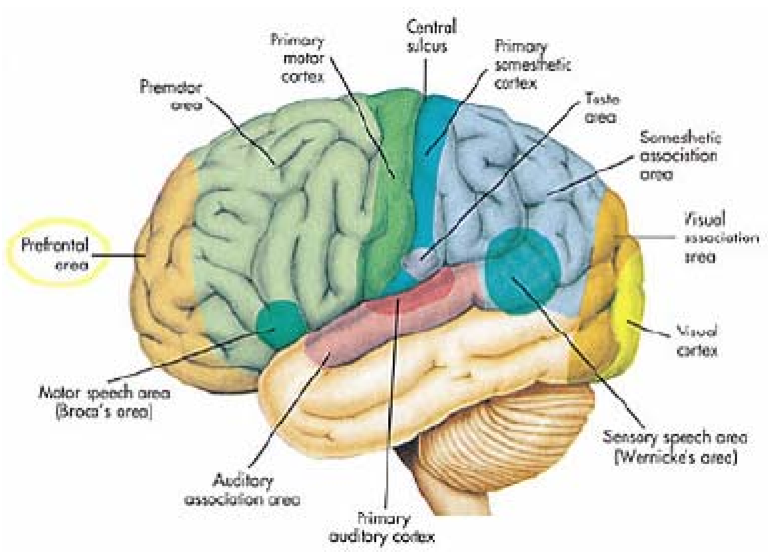

Figure 1.0 A lateral view of the brain.

Essentially a motor neuron is activated when you voluntarily decide to contract a muscle, this message is transferred down a long extension of the cell known as an axon, where the cell terminates or ends in the spinal cord. In the spinal cord the upper motor neuron connects or forms a connection with a lower motor neuron which then connects to muscle fibers. In general when you activate an upper motor neuron through voluntary intent, you activate a lower motor neuron, which then activates all of the muscle fibers it innervates. A lower motor neuron and all of the muscle fibers it innervates is known as a motor unit.

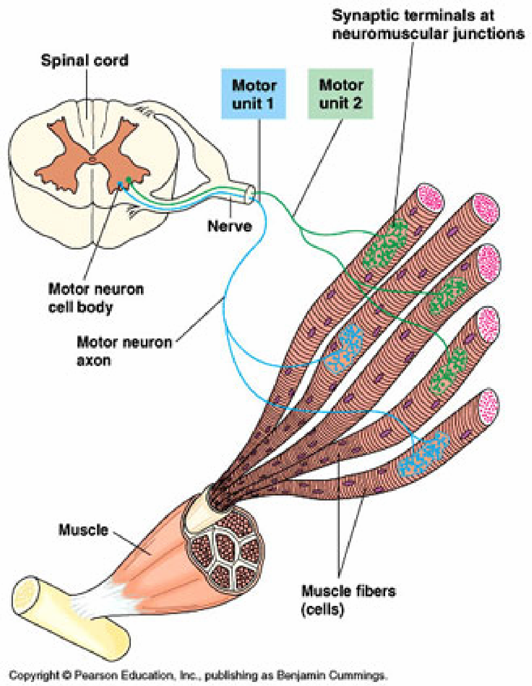

Figure 2.0 The Spinal cord, and 2 motor units directly innervating skeletal muscle fibers.
Key Points of the Motor Unit

1. **Motor Unit Size -** Motor units contain as little as a few, such as 10 muscle fibers to more than 100 muscle fibers. This is beneficial because it allows us to perform more fine movements such as putting a spin on a baseball when throwing using the smaller motor units of the hand, to gross movements such as the dead lift with larger motor units of the back. The amazing thing about the nervous system is that it can selectively choose which motor units to use during a particular movement.
2. **Motor Unit Type –** In general there are three types of motor units: (1) Slow Twitch, which contain the smaller slow twitch muscle fibers, and are used for endurance activities. (2) Fast twitch fatigue resistant, which contain fast twitch IIa muscle fibers that are larger in size, and contract at faster rates than slow twitch fibers, but that also contain strong endurance properties, though not as high as slow twitch fibers. (3) The largest Fast twitch fatigable motor units which contain fast twitch IIb fibers, which are the largest motor units, but fatigue the fastest.

The larger the motor unit the greater its capacity for growth and force production.

NEUROLOGICAL ADAPTATIONS

As stated individuals can increase in strength without increasing in the size of the muscle tissue. The mechanisms are neurologically mediated adaptations. A second reason which led to the study of these adaptations are cross training effects. Cross training occurs when an individual trains one limb, without training the second limb, and notices that their untrained limb gets stronger.

For example Ploutz et al. (1994) had participants perform a high intensity single knee extension exercise using the left leg for 3 sets of 12 repetitions for 9 weeks. The participants gained a 14 % increase in strength in the left leg. However, they only gained a

5 % increase in muscle tissue, leading the authors to suggest that many of the gains were neurological. As further evidence for this suggestion they then examined the strength of the right leg and found that it had increased by 7 %, without any growth in muscle tissue! One rationale is that we have motor programs stored within our nervous systems, much like computer programs. The motor program contains instructions to carry out a movement such as a leg extension, but just like you can play a song on your left and right speaker, you can run the motor program for the instructions for a leg extension in your right and left legs (For a review see Wilson & Wilson 2005).

The first adaptations we will discuss concern changes in muscle fiber recruitment.

INCREASED MOTOR UNIT RECRUITING CAPABILITY

The first principle of Motor Unit Recruitment is known as the ***size principle***. We have a large population of motor units within a given muscle group. These are again divided into the largest fast twitch fatigable motor units, followed by fast twitch fatigue resistant and slow twitch which are the most resistant to fatigue respectively.

Motor Units are *generally* recruited according to the size principle – This means that smaller motor units are recruited first, with the largest motor units being recruited last. The stimulus for recruitment is the speed of movement and the amount of force required in a given movement.

For example, if you can bench Press 315 pounds once, then you will recruit the largest motor units at that weight, and at 135 you will recruit relatively smaller motor units.
Or a cyclist may recruit smaller motor units on flat ground, but as they move up a hill they begin recruiting and utilizing the larger motor units.

Practical Applications

It is vital to understand that you cannot train a motor unit if you do not recruit it! This is where specificity of training effects comes into play. You will recruit motor units specific to the event you train for. For example, let's say that an individual is training to run a 5 K race and because of work they spend the majority of their time running on a flat treadmill. However the race they will run in contains a number of hills. In this case, running on a treadmill will have low transfer because the race is on a hill ridden terrain. As soon as the individual hits the hills they will begin recruiting larger motor units that they never had used in training! There are two options the individual could have used.

1. They could have run the actual race that they were required to run, in the outside environment during pre event training.

2. They could have tried to simulate the race on the treadmill by including more incline running.

In weight lifting this is also a critical concept. The reason why athletes use heavier and heavier weights is because larger force outputs require the recruitment of larger motor units, which when trained have a greater capacity for growth. This is why it is critical that athletes continue to challenge themselves with heavy weights. Another way to activate large motor units is by performing explosive movements with lighter weights.

INCREASED CAPACITY TO RECRUIT MOTOR UNITS

In a now classic study Sale and colleagues (1983) found that weight lifters could activate more motor units than untrained controls. Imagine that a muscle group has 100 motor units. An untrained individual may only be able to recruit 65 of these motor units, where as after 12 weeks of training they may be able to recruit 75-80 of these motor units. In other words your ability to recruit or call into play motor units is increased with training (Fig. 3).

Training Application

The capacity to recruit motor units is critical. In fact, as has been stated if you cannot recruit a muscle fiber you cannot stimulate it to adapt. Recruiting motor units is again however an adaptation to high force, or high velocity movements such as sprinting.

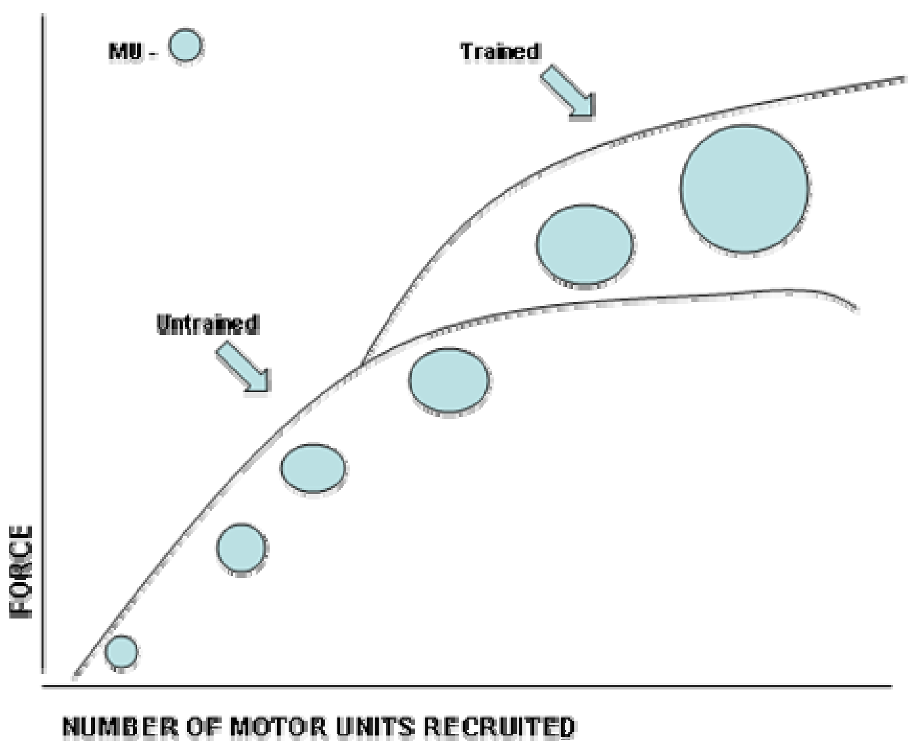

Figure 3.0 An increased capacity to recruit motor units. Figure 3 depicts motor unit recruitment before and after training. The blue circles represent motor units. The black curved line represents the magnitude or amount of motor units that can be recruited. Notice that in untrained individuals this line falls below a number of the larger motor units. With training the figure depicts that this line extends to a higher level, meaning the capacity to recruit motor units increases. Therefore, the trained individual can recruit both the smaller, and

extremely large motor units.

RECRUITING LESS MUSCLE FIBERS AS AN ADAPTATION?

An interesting adaptation is that trained individuals actually activate less motor units when performing the same training load as previously used when in an untrained state. For example let's say that your previous 10 repetition maximum was 75 pounds, but that after 12 weeks of training you can lift 100 pounds 10 times. If we measured the electrical activity in your muscles to infer motor unit and muscle activation we would see that it lowered when using 75 pounds after training. There are a number of possible reasons for these results:

1. Hypertrophy of muscle fibers results in fewer fibers needed to perform the same activity. The result is that you would get less motor unit recruitment at the same absolute loads.

While this seems to answer the question, it is only partly explanatory in nature. For example Ploutz and colleagues (1994) found that when training the right leg that the amount of muscle tissue activated was lower post than pre training when lifting the same loads as pre training. This can be seen in figure 4B. However, remember that these scientists also looked at the right untrained leg. Here you will notice that this leg also used less muscle tissue. But if they did not increase in growth how did this occur?

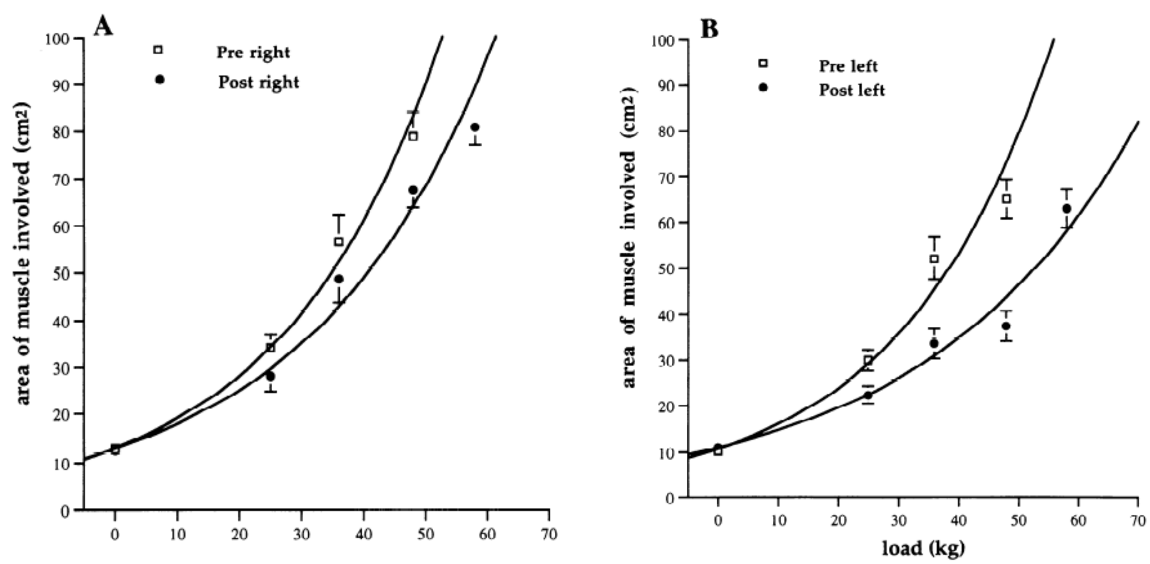

Figure 4.0. Lower muscle activation post training. Adapted from Ploutz et al. (1994)

2. It is generally thought that these participants were able to more efficiently recruit motor units. For example motor units with a greater mechanical advantage could be recruited and exert more force.

3. A third possible reason is a decrease in activity of antagonist or opposing muscle groups. Remember that antagonists muscle groups oppose the agonists or muscles which cause an action. For example when doing barbell curls, the triceps contract to stabilize the elbow joint. One adaptation is to actually lower antagonist activity. If the antagonist activity is lowered then there is not as much need to create force with the agonists. For example Carolan et al. (1992) found an increase in knee extension strength without an increase in muscle growth. At the same time the activity of the biceps femoris (hamstrings) lowered.

Practical Applications

The first practical application is the need for athletes to continue to modify their levels of effort and loads lifted. You have to realize that loads which previously taxed you will simply not activate as many motor units as it had in the past, leading to the need to continually monitor your training so that your loads are high enough to stimulate a maximal amount of fibers.

The second application concerns injury prevention. As stated, it is critical to understand antagonist muscle groups are active during movement as a mechanism to increase the stability of a joint and that there is often a decrease in antagonist activity with training. However, even if no change happened in activity in either the agonist and antagonist muscles, hypertrophy of the agonists would allow the same amount of activation to produce greater force. Technically in order to maintain the same joint stability, the antagonists would have to increase in activity because they are smaller (Fleck & Kraemer, 2004). This makes a case for training antagonist muscle groups; even though the training is not specific, overly specific training may lead to eventual injury!

POSSIBLE REVERSAL OF RECRUITMENT ORDER

Advanced athletes in sports requiring high force or power output, such as weight lifting, sprinting, and body checking in hockey may not follow the size principle. They may actually reverse motor unit recruitment order in order to maximize rate of force development. This is because fast twitch muscle fibers can shorten with greater velocities than slow twitch fibers. Therefore for greater rates of force development it is sometimes advantageous to selectively inhibit slow twitch fibers while recruiting the fibers with greatest velocity. However, evidence on this adaptation is sparse and thus far restricted to animal studies using fast movements, and in human studies using eccentric activities. More studies will need to be conducted to further analyze this possible adaptation.

ASYNCHRONOUS TO SYNCHRONOUS FIRING

There are two general types of recruiting or firing:

Asynchronous firing **–** Here motor units are not recruited at the same time; instead they are rotated in and out. In our normal everyday activities we usually use asynchronous firing. Training for endurance events causes the nervous system to favor asynchronous firing, the advantage is you can rest a population of motor units while another population works, then rotate the recovered population back in when it has recovered.

Synchronous firing – All motor units operate at once. The advantage is maximal force and power production!

Almost inevitably when you read work done on neurological adaptations you will see a reference to one of the pioneer scientists in this area of study: Dr. Millner-Brown. Dr. Brown is not only a great scientist, but a personal friend and mentor of mine. In my training for both my Bachelors and Master of Science degrees I was blessed with the opportunity to study under Dr. Brown and discuss neural adaptations extensively. Millner-Brown et al. (1975) investigated the effects of training on synchronous recruiting in thumb muscles (thenar muscles) and found that synchronization increased with training.

Occasions Where Synchronous Firing Occurs during Weight Trai*nin*g

According to Zatziorsky and Kraemer (2006) there are two ways to produce maximal synchronous firing. (1) Lifting maximal weights (1 repetition maximum). This provides the most direct stimulus for the synchronous adaptation (2) training with moderately high intensity (85 % 1-RM) until failure. Here, early in the set you recruit asynchronously, but near the last repetition as you near failure your nervous system switches to synchronous firing due to the fatigued state of the muscle and desperate need to maintain force output. In this case the last repetition somewhat mimics the demands of a 1-RM. This has the advantage of recruiting all muscle fibers possible, as well as exposing them to a long enough stimulus to trigger a growth stimulus. For maximal force production in a 1 repetition maximum, the heavier weights will be optimal, as it trains individuals to recruit and synchronously fire motor units faster than the latter technique, which actually trains the nervous system to slowly enter into synchronous firing.

Practical Applications

It is important to understand that synchronous firing will occur when the need for greater forces come into play. This is why it is important for sprinters and weight lifters, or any athlete requiring maximum force output to peak before their event by performing power cycles in which their primary focus is on generating maximal rates of force development in a synchronized fashion. In this case, higher repetition slower velocity sets will be avoided. Now, it is acknowledged that these forms of training may not be optimal for muscular growth, which is why athletes should seek to include a hypertrophy cycle in their early preparation such as in the off-season (e.g. 8-12 repetitions), but as their primary competitive event draws closer the focus should be on high force and high power activities, while dropping out higher repetitions which train an individual to asynchronously fire motor units. Of course, the current author also suggests that advanced athletes may not follow traditional periodized programs (for a detailed discussion of periodized programs see Wilson & Wilson, 2005).

INCREASED FIRING RATE

Once an athlete has recruited all of the muscle fibers in a region, they can still increase force output by increasing the rate at which the motor neuron fires (the amount of times a motor neuron can stimulate a muscle fiber to contract in a given period of time) (Fig. 5). For example, let's say that an individual could stimulate a muscle fiber to contract 3 times in X seconds with a motor neuron. With training, they may learn to stimulate it 6 times in the same period of time!

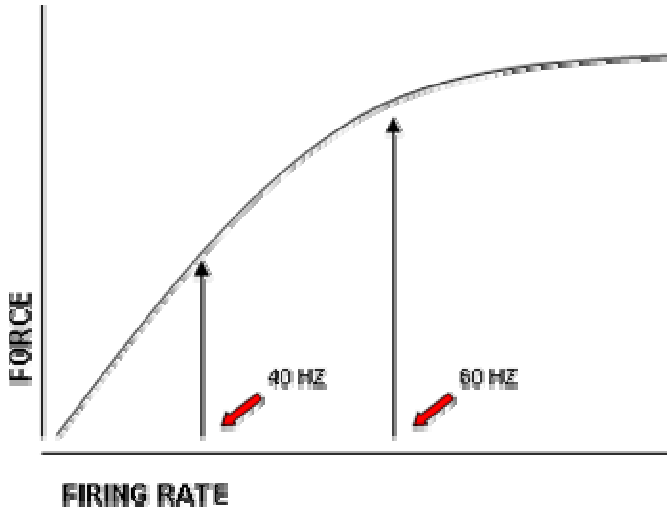

Figure 5. The relationship between firing rate and force. Note that the rate of firing simply refers to the number of times a neuron can stimulate a muscle fiber in a given period of time. Hz is a measure of this rate, and the higher the HZ, the greater the number of times a neuron can fire or stimulate the muscle fiber per unit of time.

The reason requires a brief explanation of how muscular contraction is stimulated. Within a muscle fiber are contractile filaments known as actin and myosin. When they bind tension is formed and we register it as force. The binding of myosin to actin is blocked or inhibited unless calcium is released within the cell. When a neuron stimulates a muscle fiber, it essentially stimulates storage bins of calcium known as the Sarcoplasmic Reticulum to release calcium into the cell. As calcium is released muscular contraction takes place. Relaxation occurs because calcium is actively restored in a muscle fiber. But, if a motor neuron fires before the calcium is restored, there will be a larger build up of calcium, and the contraction force will be greater. This is depicted in figure 6.0 and is known as Tetanus.

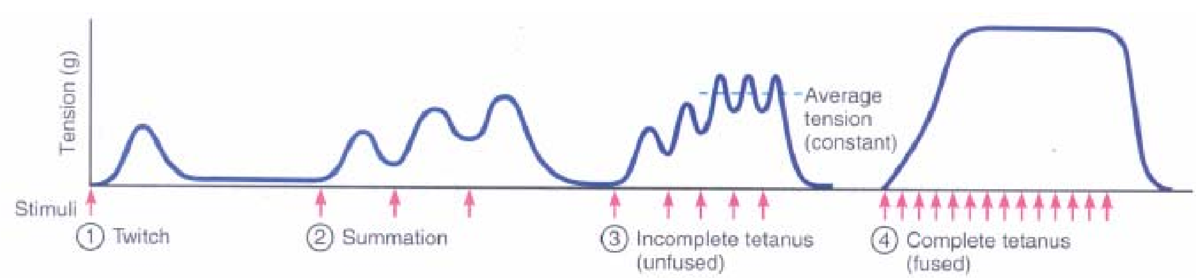

Figure 6. Tetanus. A summation of motor unit firing leads to tetanus. Adapted from Marriab et al. (2004)

With training, individuals will actually increase the rate at which they can fire motor units (figure 5.0). There are advantages and disadvantages to lower and higher firing rates.

Advantages of lower rates of firing – The muscle fiber can contract longer, and deplete less glycogen. Lower firing rates are optimal for endurance events.

Higher firing rates produce maximal force but lead to the greatest fatigue.

Training applications are similar to training for synchronous firing.

INCREASED RATE OF FORCE DEVELOPMENT

For any given period of time a trained individual will be able to reach a given rate of firing and recruitment faster than when in an untrained state (Fig. 7) (Aagaard et al., 2002). This is a power adaptation (work performed over time) and is best trained with explosive movements such as sprinting, or in weight lifting moderate weights with explosive movements (Gabriel et al., 2006).

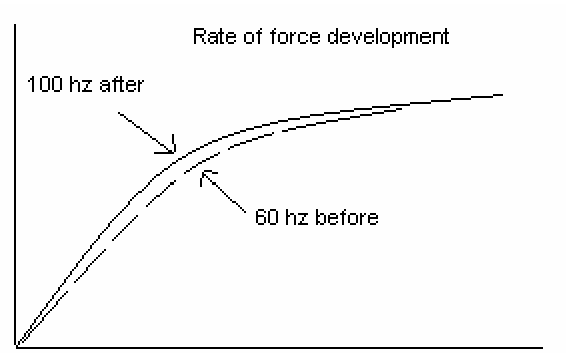

Figure 7.0 Increased Rate of force production

LOWER INHIBITORY MECHANISMS

We have all heard of the mother who lifted the car off of her child. But why is this not an everyday event? The answer is found when examining the mother after she had finished lifting the car. The results were that here ligaments and tendons were torn and her back nearly broken. You see, the body has specific inhibitory mechanisms, such as the golgi tendon reflex which inhibits our capacity to exert maximal force. Golgi tendon organs are housed within the tendons and are sensitive to increases in tension. As force output increases, tension in the tendon increases, and to prevent injury the receptors in the golgi tendon organ send signals to the spinal cord, which send signals back to the muscle to lower activity in the agonist or muscles which cause movement and increase activity in the antagonists. Training with heavier weights allows athletes to lower this neural inhibition. It is also known that this can be lowered by arousal which occurs through getting yourself 'psyched up.' This actually works to increase force output partly by lowering these inhibitory mechanisms. Often times athletes greatest weights lifted are actually during competition, when adrenaline levels are highest.

Practical Applications

Again, training is similar to synchronous training. However, this also brings into play techniques like arousal seeking imagery, which can simulate competitive events. In addition, athletes often use the golgi tendon reflex to enhance stretching. For example, if you contract your hamstrings hard, they will relax and you can stretch them further (for a detailed discussion see Knowlden, 2004).

INTRAMUSCULAR COORDINATION – OVERCOMING THE BILATERAL DEFICIT

If an untrained individual performs a leg press with the right leg at 100 pounds, and the left with 100 pounds you would think that combined he or she could lift 200 pounds. But this is not what occurs. Instead they may only be able to lift 160 pounds. This is because most of the daily activities we perform are done so unilaterally. For example, we walk with one leg at a time, we do not hop. The difference in force output between the combined limbs and actual is known as the bilateral deficit, and is overcome with training.

Practical Applications

I often see trainers having their athletes perform leg presses with one leg at a time, or performing one legged squats. However, when this occurs it is important to realize that you are actually training the athlete to perform unilaterally. In the case of the squat, when attempting to maximize force this may not be the best option. In a recent study Janzen et al. (2006) compared the effects of unilateral training of the leg extension, lat pull down and leg press on muscular growth and the bilateral deficit. The results of the study are absolutely fascinating and are summarized in figure *8.0*

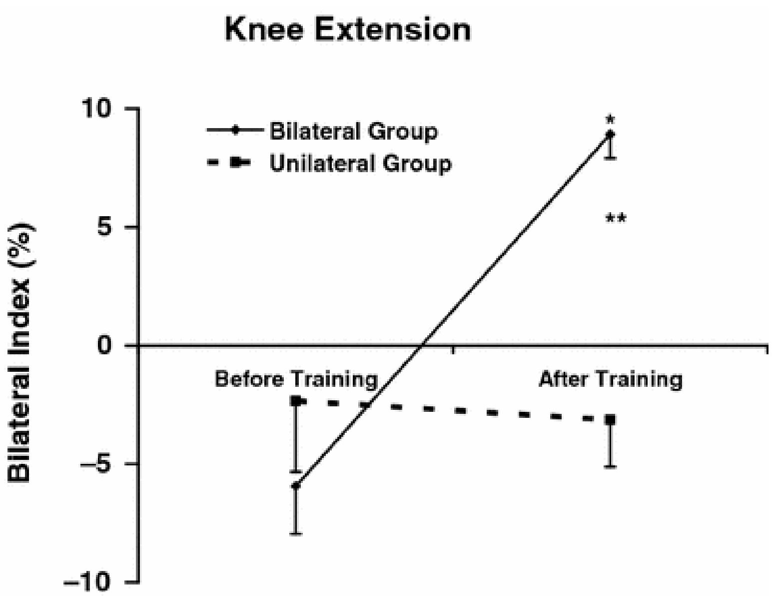

Figure 8. Comparison of Bilateral and Unilateral training on the bilateral index. Adapted from Janzen et al. (2006)

Figure 8 is a graphical depiction of the results from Janzen and colleagues (2006), and represents the change in the Bilateral index with training. Essentially the zero point on the Y or vertical access would represent a bilateral deficit of zero, where as anything below this line would represent a deficit. In contrast, if the two limbs have greater strength, the index is positive. As can be seen, the unilateral group after training actually had a tendency to increase the bilateral deficit! However, as you will note, the bilateral group were stronger with both legs. This adaptation is known as bilateral facilitation (Janzen et al., 2006). Using the leg extension as an example of bilateral facilitation, an individual may be able to lift 100 pounds with each leg separately for a total of 200 pounds. However, with bilateral facilitation they may be able to lift 215 pounds with both legs working together!

While there were no differences in lean body mass found between bilateral and unilateral conditions, there was a slight trend for the unilateral condition to have more lower body muscle gains than the bilateral condition. The rationale is that while in an untrained state, the unilateral condition would be able to lift more loads than the bilateral and therefore stimulate more growth. However, we also know that by the end of the study the bilateral group could actually lift more weight combined than the unilateral group. Therefore it is predicted that this group would be able to stimulate more growth if the study continued, than the unilateral group.

In general the practical applications are for athletes seeking to gain strength to be very careful about unilaterally training those exercises which they seek to gain strength in, such as the squat, or bench press.

PREMOTOR SILENCE

Prior to a ballistic or explosive activity such as sprinting, experimenters will often place electromyographic equipment on the participants being studied. This allows them to view electrical activity in the neurons and muscle tissue to see the relative activity level. What we know is that in trained individuals before they begin an explosive event that the electrical activity goes silent! This is known as premotor silence, and evidence suggests that it is enhanced as an athlete learns a given skill. In fact the pre motor silence period when focused on can be improved with concomitant increases in velocity of contraction (Walter et al., 1988). The rationale is that motor neurons once stimulated must recover before they can be activated again. However if they ‘rest’ or go silent prior to contraction, all of the motor units will be ready to be called into action! Again, this adaptation increases with high force and explosive training.

CHANGES IN NEUROMUSCULAR JUNCTION

The connection between the muscle fiber and neuron is known as the neuromuscular junction. It is found to increase in size with training (Fleck et al., 2004). In addition the receptors on the muscle fiber which allow neurotransmitters from the neuron to communicate with it increase in number. Finally, it should be noted that the muscle fiber and neuron do not actually touch, but as training increases the distance between the two shortens, allowing for more rapid communication (Fleck et al., 2004). What is known is that these changes occur in both endurance training and strength training, but that they are more robust in strength trained individuals.

TIME COURSE OF NEUROLOGICAL ADAPTATIONS

The body is like students and electricity: “Always seeking the path of least resistance.” It is important to realize that muscle tissue is extremely metabolically costly to maintain. Therefore the body will adapt first by making neurological adaptations, but as time increases it becomes more and more reliant on hypertrophic or growth changes (figure 9).

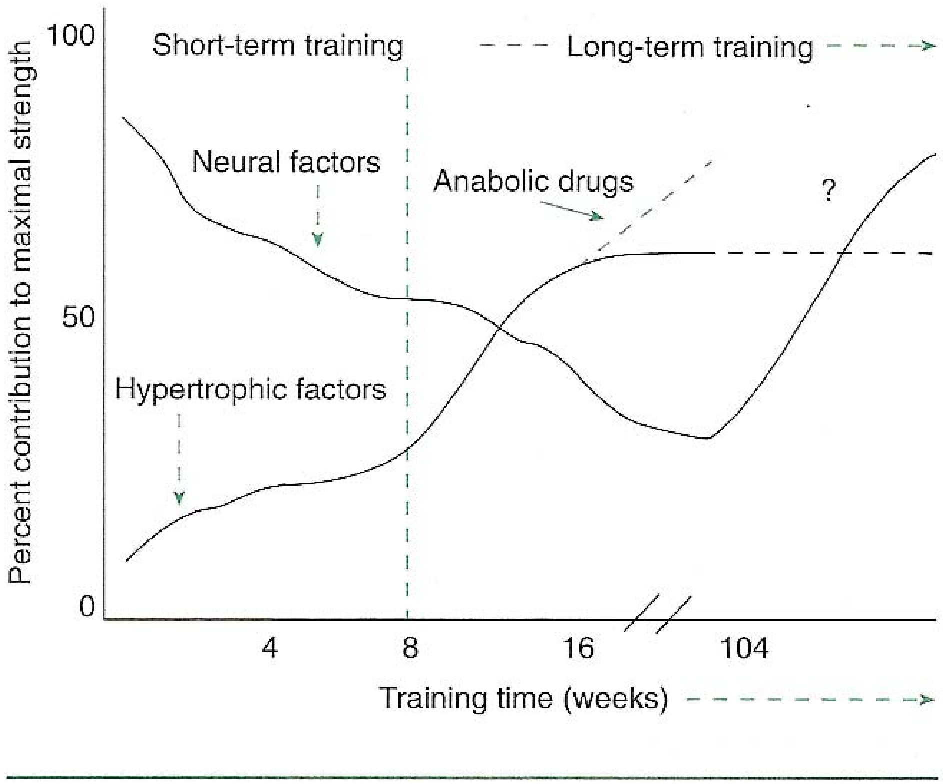

Figure 9. Neurological and Muscular changes over time in training. Adapted from Fleck and Kraemer, 2004

You will note the interesting nature of the graph. During the first period of training, neural adaptations dominate, but then hypertrophic gains dominate. Note however that with long term training that neural adaptations may again increase in prominence. This relationship is suggested because elite athletes with well over a decade of training experience, who compete in world class events still can increase in strength without increasing in muscular hypertrophy.

However, I need to make it clear that the latter part of this graph is full of more questions than answers and therefore, needs a great deal of investigation to clarify exactly what really occurs in the long term. I recently spoke to my colleague Gabriel Wilson, who has published and worked with some of the top Sports Psychologists in the world. Gabriel suggested that that there are numerous theories which could explain changes in strength in advanced athletes besides changes in motor recruitment. For instance, he posited that elite athletes, who experience plateaus in training, may try to incorporate methods other than practice to improve performance, including psychological techniques such as imagery, or arousal regulation; they may also focus greater attention to minor details in technical aspects of the lift being performed. Secondly, he postulated that perhaps instead of showing graphs in which hypertrophic and neural factors improvements decrease, that perhaps the graph should actually show them both reaching asymptotes, or stages in which gains are extremely slow. The implication is that neither parameter ever really stops contributing to strength gains, but that gains are negatively accelerating providing less and less return for more and more effort. At this point, it is nearly impossible to say what actually occurs chronically, accept that we know in elite athletes that gains in strength can occur absent of hypertrophy.

Practical Applications

The neural hypertrophic relationship is not only determined by time, but also by the complexity of the exercise. It is thought that neural adaptations precede hypertrophic adaptations. It is also known that in smaller exercises like leg extensions, that neural adaptations occur more rapidly then in squats. For this reason, athletes seeking hypertrophy may add in many auxiliary exercises which lower the neural control component through simple movements, which may allow them to actually enhance muscle tissue growth at a faster rate, then if they had only used more complex movements. For competitive weight lifters however, it is not generally recommended to have leg extensions or isolation movements. However, squats can serve as excellent auxiliary exercises to their primary exercises such as the clean and jerk.

SPIRITUAL APPLICATIONS

The other day I was up at 6 in the morning on a Saturday collecting data for an experiment in our exercise physiology lab here at FSU. Tired and weary, I suddenly received a burst of energy when I realized that I was doing what it is I had endeavored to do since childhood: To explore and discover the unknown. This is what science is about. I have the unique opportunity to actually be a full time scientist. And I have to admit it is a wonderful opportunity in which I have been able to explore one of God's greatest creations – the human body. One needs to look no further than the nervous system and its intricate adaptations to see what the Psalmist meant when he stated
"*I will praise thee; for I am fearfully and wonderfully made" Psalms 139:14*

One of the key spiritual applications to this paper is to simply take a step back and not only be in awe of the incredible adaptations that the nervous system makes in response to stress, but more importantly to be in awe and give thanks to the one who created this system: The Lord Jesus Christ.

John 1:1-4

> ***1*** In the beginning was the Word, and the Word was with God, and the Word was God. ***2*** The same was in the beginning with God. ***3 All things were made by him; and without him was not any thing made that was made.*** ***4*** In him was life; and the life was the light of men.

FINAL THOUGHTS

It can be seen that the nervous system adapts through extremely complex mechanisms, which augment force output in athletes. It was the goal of this article to summarize these adaptations. It is the intent of this author to integrate these points in a new series of articles which address each acute training variable separately. Variables discussed include exercise intensity, exercise choice, frequency, rest periods, and volume. Not only will these variables be discussed from a physiological standpoint, but also a neurological standpoint. To this end, the reader of this article will be extremely well prepared to take their training to a new level.

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