Mechanical Model for Analyzing Adaptation to Training

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Introduction

According to the Principle of Specific Adaptation to Imposed Demands (SAID), our bodies adapt in very specific ways to the types of stresses we apply to them during our training [1]. This is not limited to muscle tissue, but also includes subcellular components within muscles as well as connective tissues and various bodily systems. The SAID principle suggests that we should train our bodies according to our training goals. If you want a specific adaptation of your body to occur, then you need to impose demands that stress the bodily systems that lead to the desired adaptation.

Certainly, we all know that mechanical loading of our muscles is one of the key principles on which our training should be based if muscle mass is our goal. Question is: How should we implement this mechanical loading of our muscles? Should we use a very low volume and very high intensity, or should we go for high volume with a lower intensity? Should we train frequently, or should our training be infrequent? When confronted with such questions, many a new lifter will turn to popular training programs in search of the answers.

Of course, there are a wide variety of training programs available, all emphasizing particular approaches to muscle growth. Lower volume training programs, such as High Intensity Training (HIT) and Heavy Duty (HD), recommend taking every set to momentary muscular failure so as to recruit as many muscle fibers as possible before finishing the set [2]. On the other hand, Hypertrophy-Specific Training (HST) suggests that that all types of muscle fibers are recruited when the muscles are exposed to heavy enough loading [3]. With HST, training to failure is avoided in favor of training more frequently with heavy weights, and with training volume spread uniformly throughout one's training cycle. Higher volume programs such as German Volume Training (GVT) emphasize lower weights with much more training volume [4]. The idea, here, is that muscle growth is encouraged by exposing the muscles repeated bouts of a loaded movement.

In view of all the different types of training regimens available, how can we make a truly informed choice? For instance, when we want to build new muscle as fast as possible we'll need to train differently than when we want to build limit strength. Moreover, when we want more aerobic endurance we'll have to train differently than when we want more muscle mass. In order to make informed decisions about which training program to use, we need to know how our muscles function.

Muscle function is usually described in terms of the actual physiological structure of the muscle fibers comprising muscles, as well as the bodily systems that interact with the muscle fibers. While this is indeed accurate, it can also obscure the information that we need in order to select a training program. Being a physics/engineering type of guy, I find complex topics easier to understand when I can find a simple mechanical analogy, or model, and then break it down into a group of systems performing specific functions. In the following sections, our objective is so see if we can come to any conclusions about our training by analyzing a simple mechanical model that conforms to the SAID principle.

Model of Motor Unit

Muscles are comprised of many muscle fibers. When the muscles are needed for exerting forces against objects, such as a barbell, the brain sends signals to the muscles via nerves. These signals cause the muscle fibers to shorten, or contract. As pointed out above, the precise science underlying muscle physiology is very complex. For this reason, we'll turn to the simpler concept of "motor units." Of course, if you'd like to know more about muscle physiology, "How Muscles Work" [5] provides a detailed and nicely animated presentation on muscle function.

A motor unit is defined as all the muscle fibers that are innervated by a single nerve cell, called a neuron [1,6]. We'll rely on a mechanical model of a motor unit, shown in Figure 1.

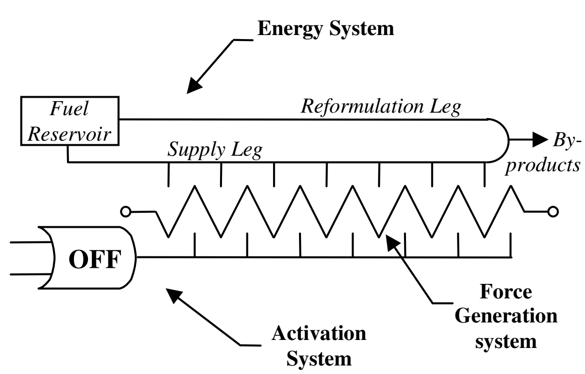

Figure 1: Mechanical Motor Unit Deactivated

As you can see, the mechanical motor unit has three basic systems: an Activation System, an Energy System, and a Force Generation System. The Activation System is similar to the neuron that innervates a real motor unit. When the Activation System is "OFF," as shown in Figure 1, the mechanical motor unit is relaxed and produces no force. When the Activation System is "ON," however, the mechanical motor unit contracts, creating a mechanical *F*, as shown in Figure 2.

The Force Generation System is the component of the motor unit that creates the mechanical force *F* by contracting when the Activation System is turned ON. The Force Generation System is analogous to myofibrils, which contain myofilaments that actually shorten during the contraction of real muscle fibers.

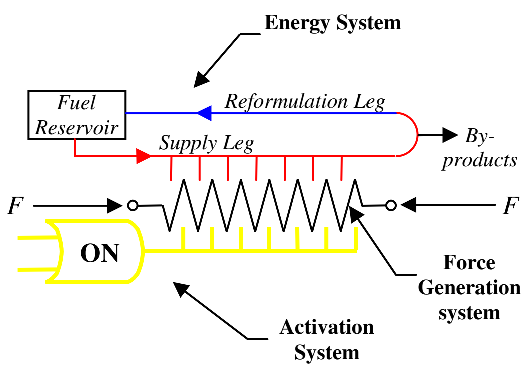

Figure 2: Mechanical Motor Unit Activated

An important point to notice about the mechanical motor unit is that the Activation System transmits pulsed signals. Each pulse causes the Force Generation System to contract momentarily and then relax. In the case of a real motor unit, this is referred to as a "twitch" [6]. When a constant output force is required, the Activation System passes a large number of pulses each second, which causes the Force Generation System to twitch accordingly. In essence, the faster the Activation System pulses, the faster the Force Generation System twitches, and the larger is the output force produced. This phenomenon is called "rate coding" and it has a direct bearing on the level of strength of the motor unit [6].

The Energy System supplies and manages the fuel required by the Force Generation System for producing a force when the Activation System is in the ON state, as shown in Figure 2. For a real motor unit, the Energy System includes adenosine triphosphate (ATP) and the three pathways of ATP reformulation: creatine phosphate (CP), glycolysis, and oxidation [1].

As you can see, the Energy System includes a Fuel Reservoir, a Supply Leg, a Reformulation Leg, and a Byproducts Leg. The Fuel Reservoir represents onsite storage of fuel which is immediately available for transport to the Force Generation System via the Supply Leg when the Activation System is switched to the ON state. While generating an output force, the Force Generation System produces exhaust products, some of which can be reformulated into useable fuel. The Reformulation Leg reformulates the useable exhaust products for use all over again. Exhaust products that cannot be reformulated are removed by the Byproducts Leg.

Upon comparing Figure 2 with a real motor unit, the Fuel Reservoir and the Supply Leg represent stored ATP that's supplied to the myofibrils during contraction, and the Reformulation Leg represents the three pathways of ATP reformulation. The Byproducts Leg represents the accumulation and removal of metabolic byproducts of muscle contraction, such as lactic acid, carbon dioxide, and water.

Applying Stress to the Mechanical Motor Unit

Now that we have an understanding of the various components of our mechanical motor unit, let's see what happens when we apply stress to these components. In the "real" world, machines wear out and eventually break when they encounter continual stress. Our bodies are different; they have the ability to adapt to stress so as to counteract it in the future. To take this into account, we'll note that whatever component of the mechanical motor unit that's stressed will become more efficient at performing its function. That is, we'll apply the SAID principle to the mechanical motor unit.

Of course, we all know that with our real bodies, adaptation isn't limited to only one body part or another. Training causes adaptation of the muscles as well as several other bodily systems that function in concert with the muscles. But we're interested in specifics here; so we'll focus on the most obvious adaptations.

Each system of the mechanical motor unit can limit the motor unit's function under stressful conditions. On the other hand, the SAID principle tells us that each system that's stressed adapts so that it gets better at performing its function. The system that's stressed most depends on the type of demands placed on the motor unit. Initially, there are three primary training scenarios that we're interested in: supporting a light weight for a long time, supporting a heavy weight for a short time, and supporting a moderate weight until failure of the motor unit. The following table summarizes the functions of the motor unit's systems and the primary adaptations one can expect when those systems recover from imposed stress.

System	Function	Adaptation
Activation	Transmits pulsed signals to Force Generation System.	Improved rate coding and tolerance to byproducts.
Force Generation	Exerts mechanical forces against imposed loads.	Improved output force.
Energy	Supplies fuel to Force Generation System.	Improved fuel supply and reformulation efficiency.

Suppose we use the mechanical motor unit to support a light weight for a long period of time. Which systems of the motor unit are most impacted by this level of stress? It's not the Force Generation System, because the weight isn't very heavy. Nor is it the Activation System for essentially the same reason. However, the Energy System undergoes considerable stress as it works to keep fuel flowing to the Force Generation System. Since the motor unit adapts to imposed demands, the Energy System will become more efficient at supplying fuel to the Force Generation System.

Applying this to our training, we can see that the above scenario is analogous to aerobic endurance training. Frequently training in this manner increases the body's ability to supply the muscles with ATP. All bodily systems involved in this type of activity will adapt accordingly. For example, the cardiovascular system will become more efficient at supplying oxygen to the muscles for use in ATP reformulation.

Now suppose that the mechanical motor unit supports a very heavy weight for a short period of time. This directly stresses the Force Generation System. So long as the weight is heavier than whatever weight has been previously encountered, the Force Generation System will adapt. When the Force Generation System recovers, it will become more accustomed (i.e., conditioned) to the heavy weight. Thus, the Force Generation System will become increasingly capable of supporting the weight in the future. In the case of a muscle, the cross-sectional area (CSA) of the myofibrils will increase, making the muscle bigger.

Supporting the heavy weight also stresses the Activation System. In order to see how the Activation System is affected by the heavy weight, recall that the motor unit's strength output is dependent not only on the conditioning of the Force Generation System, as discussed above, but also on the level of rate coding (i.e., the number of pulses transmitted per second) that the Activation System can endure. If the stress on the Activation System is greater than what has been previously experienced, the Activation System will be forced to adapt. As a consequence, the motor unit will become stronger.

Applying this model to our training makes it straightforward to see that lifting heavy weights for short periods (i.e., without hitting momentary muscular failure) will cause the muscles and the nervous system to adapt. The CSA of myofibrils will increase, and the level of rate coding will improve. Stated simply, your muscles will get bigger and your strength will increase.

Next, let's consider what happens when we use the mechanical motor unit to support a moderate weight for a period of time long enough for the motor unit to momentarily fail. Which systems are affected by this type of stress? Certainly, the Force Generation System will be stressed if the weight is greater than whatever weight has been previously encountered. Likewise, if the level of rate coding is greater than what the Activation System has previously endured, the Activation System will be stressed, as well. The primary stress due to failure, however, is on the Activation System as it continues to work in the presence of increasing levels of byproducts. As the Force Generation System continues supporting the weight, the level of byproducts will continue to increase to the point at which the Activation System is squelched [1,6]. The motor unit will then fail until the byproducts of contraction are cleared.

Upon applying the above analogy to failure training in the gym, it's easy to see that our muscles will grow so long as the weight we use is greater than the level of conditioning of our muscles. It's also easy to see that training to failure forces our nervous system to continue working as levels of metabolic byproducts of contraction continue to increase. Indeed, doing this improves the level of rate coding that we can muster and our tolerance to metabolic byproducts. These adaptations of the nervous system lead primarily to increased strength.

We have applied the mechanical motor unit to a few training extremes and discussed the corresponding adaptations. The table below summarizes the systems that are affected by these training conditions and the corresponding bodily adaptations we can expect.

Training Condition	**Primary System Affected**	**Corresponding Bodily Adaptation**
Light Weight Long Time	Energy	Cardiovascular system and oxidative ATP reformulation.
Heavy Weight Short Time	Force Generation Activation	CSA of myofibrils and improved rate coding.
Heavy Weight Failure	Force Generation Activation	CSA of myofibrils and improved metabolic byproduct tolerance.

Applying the Mechanical Motor Unit to Training Programs

Let's apply what we know about our mechanical motor unit to three popular training programs and see what types of adaptations we can expect.

With HIT, you generally use weights ranging between 70-80% of your 1RM weight for each exercise, and every set is taken to momentary muscular failure [2]. One popular way to perform HIT is by starting with your 8RM weight and then working until that weight becomes your 12RM weight. At that point, you add more weight and then work to make this newer, heavier weight become your 12RM weight.

The Force Generation System will adapt so long as the weight exceeds the current level of conditioning. Taking sets to failure, however, forces the Activation System to operate in the presence of byproducts from the Force Generation System until the Activation System actually stops working. This level of stress on the Activation System requires recovery time. Since the Activation System recovers more slowly than does the Force Generation System [1], further adaptation of the Force Generation System must wait for the Activation System to catch up. As the Activation System becomes conditioned to failure training, its level of rate coding and tolerance for byproducts will improve. Unfortunately, recovery of the Activation System becomes a bottle-neck which slows down the rate with which greater loads can be applied to the Force Generation System.

Drawing an analogy with our training suggests that using HIT will lead to muscle growth in the beginning, while we're deconditioned to the loads. Training to failure, however, requires time for the nervous system to recover before more weight can be added. Since the nervous system takes longer to recover than do the muscles [1], the frequency with which the muscles are loaded must be lowered to accommodate the recovery of the nervous system. As a result of this delay, the muscles will quickly become conditioned to the loads, and growth will begin to plateau.

With HST, you use weights ranging between about 45-95% of your 1RM weight for each exercise. Weights are progressively increased throughout your training. HST requires a period of deconditioning to ensure that all weights are greater than what the Force Generation System has previously encountered. Moreover, sets are not regularly taken to failure, thus reducing the time required for the Activation System to recover. This allows for more frequent loading of the Force Generation System. Since HST focuses on progressively loading the Force Generation System with heavier weights and the Activation System isn't acting as a bottle-neck, the Force Generation System experiences substantially unhindered adaptation [3].

Since HST keeps the nervous system's recovery time minimized, you're able to frequently load your muscles with more and more weight. The required deconditioning period ensures that your muscles aren't accustomed to the weights, and thus every weight is a "new" weight [3]. It's straightforward to see that loading the muscles with greater weights will cause the muscles to grow in size and strength. And, by keeping the nervous system's recovery time under control, the muscles can be loaded much more frequently than would be otherwise possible. This maximizes the amount of muscle growth that can be achieved in the shortest amount of time. So it would seem that HST really is, indeed, a hypertrophy-specific approach to training.

Your objective with GVT is to perform 10 sets of 10 repetitions with a weight of about 60% of your 1RM weight for compound exercises [4]. This requires a high level of work performed with low to moderate weights. Starting from a deconditioned state, the Force Generation System will adapt to the weights. However, momentary failure will be encountered on some of the later sets, which will require time for the Activation System to recover and adapt. Since the Activation System adapts more slowly than does the Force Generation System, the weights can be increased only once the Activation System catches up. This slows down the rate with which the Force Generation System can be loaded with heavier loads. Moreover, the high level of work in GVT stresses the Energy System, which also must adapt before more weight can be applied to the Force Generation System. In essence, the recovery time of both the Activation System and the Energy System hold up the progressive loading of the Force Generation System. This slows down the level of adaptation experienced by the Force Generation System.

It's easy to see that your ability to continually increase the weights you use with GVT will be limited not only by the recovery of your nervous system, but also by the time required for improved efficiency of the pathways of ATP reformulation. Once your muscles become conditioned to the weights, the rate of muscle growth that you experience will begin to slow, leading to an eventual plateau.

Final Thoughts

We have demonstrated that by using straightforward analysis of a simple mechanical system that obeys the SAID principle, we can come to definite conclusions about the types of improvements we can expect from various forms of training. In essence, we found that progressive loads lead to increased muscle size and strength, working to momentary muscular failure improves strength and tolerance to metabolic byproducts, and working with high volume leads to improvements in the three pathways of ATP reformulation, as well as tolerance to metabolic byproducts.

Upon applying the mechanical motor unit to HIT, HST, and GVT, we found that all three training programs lead to some degree of improvement in muscle size and strength. With HIT, however, progressive loading of the muscles is slowed because the nervous system takes longer to recover from failure training than do the muscles. This delay hinders muscle growth. GVT seems to have a similar problem; namely, progressive loading of the muscles must wait for the nervous system to recover from failure training and for improved efficiency of the pathways of ATP reformulation. Slowing the progressive loading of the muscles decreases the level of muscle growth that can be expected.

On the other hand, HST places a central emphasis on progressive loading of the muscles while minimizing the recovery time of the nervous system. Without having to wait for the nervous system to recover, the muscles are free to be frequently loaded with progressively greater loads. On this basis, it would seem that HST offers the greatest potential for muscle growth in the shortest possible time.

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