Influence of the endocrine system on resistance training adaptations

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All resistance-training programs are not the same in their adaptive responses (26). While most heavy resistance-training programs, if properly prescribed, will result in strength and size gains, the magnitudes of the gains are different between programs. Empirical evidence indicates that strength or power increases are not always related to the percentage gains in muscle size. For example, one can gain strength and power with little or no change in muscle size or body weight.

A limited amount of scientific work with bodybuilders, powerlifters and weightlifters has hinted at this phenomenon (19, 33). While strength and size gains occur simultaneously with heavy resistance training, different program configurations may produce different magnitudes of gain in either the muscle's strength/power aspects of adaptation or the adaptation of increased muscle size. Understanding the differences in program design and how the physiological systems can be manipulated to produce these different effects is paramount to successful exercise prescription (27).

The endocrine system can dramatically differ in its response to a resistance training stress (23, 24). Hormonal responses can also be quite different depending on the characteristics (i.e., acute program variables) of the program design (strength versus size). The NSCA's concept of "bridging the gap" between the scientist and the practitioner means that the scientist learns about the responses and adaptations to resistance exercise, and the practitioner takes the basic knowledge and applies it to making up the best exercise prescription consistent with the athlete's training goals.

Understanding the physiology of the athlete's training goals and then matching them with the correct exercise prescription is vital to optimal body development for a particular sport performance. This article will discuss some of the issues involved with the development of muscle tissue and will overview some hormonal responses of testosterone and growth hormone to resistance exercise and training.

**Muscle Tissue Development**

The remodeling of muscle tissue after exercise is a complex process involving a multitude of events, ranging from cell receptors interacting with various hormones to the DNA production of new contractile proteins. The exercise prescription, nutrition status, nervous system and genetic capabilities of the cell to produce protein are just a few factors that are vital for optimal tissue development. The endocrine system plays an important role in augmenting the cellular processes involved in the remodeling of the muscle cells (9, 10, 34). With so many hormones, the complex interaction of the various glands and secretions provides for an intricate communication system between the exercise stimulus and the adaptive response.

This communication network is short-circuited by anabolic drug use, which eliminates the natural links of the body's hormones. The responsiveness of the endocrine glands to the resistance exercise stimulus is altered. This creates a situation where the cell responses are cued to a pharmacological level of externally provided substance rather than a physiologically timed response and release of the body's hormones. In essence, drug use negates the body's natural anabolic hormonal response.

Concomitantly, training adaptations of the endocrine glands and biological timing responses between
the muscle alterations and endocrine system are lost. The endocrine glands, similar to muscle, go through a training adaptation, and time is needed to develop the physiological links between the exercise stimulus and the various mechanisms that contribute to the development of neuromuscular adaptations. In addition to the known and unknown risks of anabolic drug use, the lack of a training stimulus to the endocrine system's glands, along with the loss of the natural hormonal interactions, are points that need to be considered.

Hormonal increases in response to resistance exercise take place in a unique physiological environment. Significant amounts of force from performing heavy resistance exercise are translated to the muscle fiber and cell membranes. Such a stimulus causes alterations in the shape and function of the membrane, allowing increased nutrient uptake by the muscle cell. Additionally, mechanical forces from the heavy resistance exercise cause disruptions in muscle fibers, which are crucial for the initiation of a remodeling process in muscle.

Tissue repair mechanisms are activated as a part of the recovery process, in which remodeling is initiated to various extents after each exercise session. It appears that the mechanisms involved with tissue remodeling after normal resistance exercise stress are different from the repair that takes place after injury or severe tissue damage. In the case of muscle tissue remodeling, the magnitude of damage and inflammation is not as great as observed in muscle damage studies (1).

This ongoing process of disruption from exercise and remodeling with rest is really not noticed by an individual unless too much exercise is performed or one is not accustomed to a particular exercise stimulus (e.g., heavy eccentricities) (1). Such tissue conditions consequent to heavy resistance exercise provide available sites of interactions with various hormones. The stimulus, magnitude of release and timing of the hormonal events in relationship to the alterations of the muscle with resistance exercise are key factors affecting the adaptation of tissue in general and, more specifically, muscle. A variety of hormonal mechanisms could theoretically influence the growth and remodeling process of various body tissues (e.g., muscle, bone, and connective tissue) over the course of a resistance-training program (25).

**Endocrine System Response to Resistance Exercise**

It is well known that strength and power training presents a potent exercise stimulus to the entire musculoskeletal system. This type of exercise stress activates a wide variety of physiological mechanisms involved with the activation of muscle and the subsequent adaptation of almost every system in the body. One of the physiological systems shown to be responsive to acute heavy resistance exercise stress is the endocrine system (24). Chronic training adaptations in the endocrine system have been related in part to improved force production (13).

Resistance-exercise stimulus in resistance exercise is made up of a combination of variables (8, 27, 29). In general, the exercise choice dictates the mode of contraction, musculature used and other biomechanical aspects of each exercise. The order of exercise influences the metabolic demands and the fatigue state of the muscle before the start of an exercise. The resistance used for the exercise defines the motor-unit recruitment patterns, metabolic demands and velocity of movement. The number of sets helps to determine the volume (sets x repetitions x load) of resistance exercise. Finally, the length of rest periods between sets and exercises affects the metabolic demands, resistance that can be lifted and recovery status of the muscle.

Each of these five program variables interact to define an acute exercise stimulus for a resistance exercise protocol. Therefore, the endocrine responses and adaptations would be linked to the configuration of the specific resistance-exercise stimulus (choice of exercise, order of exercise, load, etc.). It is obvious that a multitude of protocols are possible when dealing with these acute program variables. Still, it is important to realize that the magnitude of the hormonal response will be related to the specific configuration of the chosen exercise protocol (e.g., strength training versus muscle vs. small muscle group exercise choice).

Several factors are important for the interaction of hormones with muscle and other tissues of the body (25):

- When exercise acutely increases the blood concentrations of hormones, regardless of mechanism, a greater probability of interaction with receptors is possible.
- Because adaptations to heavy resistance exercise are anabolic in nature, the recovery mechanisms involved are related to tissue remodeling and repair.
- Mistakes in exercise prescriptions can result in a greater catabolic effect (e.g., overtraining) or an ineffective exercise program. Accordingly, hormonal mechanisms either will adversely affect tissue development or will minimally activate mechanisms that augment the adaptation or changes initiated by the neural recruitment and the force production demands of high-intensity resistance exercise.

The total of all such factors is thought to be the stimulus for the phenomenon of exercise-induced muscle hypertrophy. In addition to
size increases, the strength and power performance of the body is also related to other factors (e.g., neural recruitment). In a study by Patton et al., it was shown that leg power was not explained by muscle fiber size or type alone (37). Such data indicates that the production of power is a more complex phenomenon and is related to more than just a single factor such as the size or type of the muscle fiber (37). The various hormonal mechanisms probably respond differently in trained and untrained individuals (13). In addition, certain hormonal mechanisms (e.g., testosterone) may not be fully operational in both males and females. It now appears that a wide array of hormonal mechanisms with differential effects based on program design, strength/power fitness level, age, gender, genetic predisposition and adaptational potential appear to provide myriad possible adaptation strategies needed for the maintenance or improvement of muscle size, strength or power.

The following discussion is only a basic overview of two important hormones involved with resistance-training adaptations. Many more are involved, and information on this topic has been published elsewhere (3, 23, 24, 28). In addition, by promoting the best possible combinations of the resistance-training stimulus for a given goal, more optimal and effective training programs will be prescribed. Training dedication, discipline and hard work will never be eliminated from the natural methods, but greater satisfaction can be realized in seeing the long-term development of the athlete maintained with appropriate training techniques. In a new era when optimizing training time is essential for the best results, a mistake in program design can limit optimal progress.

**Testosterone**

The differences in muscular development between males and females have been attributed to the anabolic actions of the male sex hormone testosterone. The primary and secondary sex characteristics of a male also depend on this hormone's androgenic actions. Hypothalamus-releasing hormones stimulate the secretion of luteinizing hormone (LH) and follicle-stimulating hormone (FSH). LH stimulates production of testosterone in the cells of the testes. FSH appears to help LH in promoting production of testosterone. In females, smaller amounts of testosterone are produced by the ovaries and the adrenal glands (2, 3, 22, 23). Some women may have higher circulating levels of testosterone (still many times lower than any male), and this is typically due to the greater production of testosterone from the adrenal glands.

Increases in peripheral blood concentrations of total testosterone have been observed during and after many types of high-intensity exercise (11). The possible actions of testosterone in anabolic actions have been previously reviewed (3). It appears that its role in the augmentation of the release of other hormones (e.g., growth hormone) and interactions with nervous tissue may be more important than its direct anabolic actions on muscle. Because almost all hormones, including testosterone, increase in response to endurance exercise, the role the hormone plays in the acute and adaptive response of the muscle cell may depend on the cellular environment produced by the resistance exercise previously discussed. Thus, increases must be viewed in relationship to the type of exercise stimulus that produced them.

Increases in serum total testosterone appear to occur in exercises that use large muscle group exercise (e.g., deadlift versus bench press) (7, 12). Heavy lifting also appears to promote increases in testosterone, despite a lack of response in growth hormone (31, 32). This suggests that the inter-face of testosterone with the nervous system's tissue in males may be an important physiological aspect for adaptation to heavy resistance exercise. The various acute post-exercise responses of serum total testosterone to heavy resistance exercise in a study by Kraemer et al. (32) are presented in Figure 1.

Fahey et al. were unable to demonstrate significant increases in high school-age males in serum concentrations of total testosterone (7). A recent report by Kraemer et al. suggests that increases may occur if the resistance-training experience is two or more years (30). In this study, competitive Junior Olympic weightlifters served as subjects. The group with less than two years of experience demonstrated no increases, while the group with more than two years of experience observed increases in response to a resistance exercise protocol. No differences in age, size, strength or any other variable were observed between the two groups, nor explained this exercise-induced ability to release testosterone. This study supports the possibility that intense resistance training may alter the physiological release of testosterone in younger males.

Scant data are available concerning the acute heavy resistance exercise responses of free testosterone. Hakkinen et al. observed that free testosterone remains unaltered or decreases after resistance–exercise training sessions (14-20). The free hormone hypothesis supports the idea that only the free hormone is transported into the target tissues. Still, the validity of such a hypothesis has not been established, and it appears that the bound hormone could significantly influence the rate of hormone delivery and thus have a great deal of physiological significance (6). Many other factors affect the eventual effects of testosterone's tissue interactions,
Figure 1. Responses of serum testosterone to heavy resistance protocols.

Exercise Order | Series 1 (S 5/3) | Series 2 (H 10/1)
--- | --- | ---
Bench press | 5 RM x 5 | 10 RM x 3
Double-leg extension | 5 RM x 5 | 10 RM x 3
Military press | 5 RM x 3 | 10 RM x 3
Bent-leg incline sit-up | 5 RM x 3 | 10 RM x 3
Seated row | 5 RM x 3 | 10 RM x 3
Lat pull-down | 5 RM x 4 | 10 RM x 3
Arm curl | 5 RM x 3 | 10 RM x 3
Leg press | 5 RM x 5 | 10 RM x 3

All exercises performed on a Universal weight machine except for bent-leg incline sit-up and arm curl, which used free weights. The rest control for series 1 used 1 minute rests (S 5/1) and the load control used a 10 RM (S 10/3). In series 2 the rest control used 3 minutes rest (H 10/3) and the load control used a 5 RM (H 5/1). Same exercise order for every protocol. Modified from (32).

from the regulation of testosterone by availability of binding proteins to interactions with the cell receptor (38). Hakkinen et al. have demonstrated that changes in sex hormone-binding globulin (SHBG) and SHBG: testosterone ratios are correlated to isometric leg strength, and have reflected the patterns of force production improvements in leg musculature (14-20).

Training Adaptations
Comparing subjects with little or no resistance-training experience and subjects who had at least two years of experience, Fahey et al. were unable to show significant differences in serum testosterone concentrations before or after an exercise protocol consisting of five sets of five repetition maximum (RM) deadlifts (7). This indicated that the testosterone appears similarly responsive after maturation in adult males. Conversely, Hakkinen et al. have demonstrated that over the course of two years of training by elite weightlifters, resting serum testosterone concentrations do increase (19). This was concomitant to increases in FSH and LH.

While the testosterone changes showed remarkable similarities to the patterns of strength changes, the SHBG: testosterone ratio mir-
Figure 2. The responses of serum growth hormone are presented the same scheme as for the testosterone responses in Figure 1. Modified from (32).

Rored strength changes even more closely. It is interesting to hypothesize that in athletes with little adaptive potential for changes in muscle hypertrophy (i.e., highly trained strength athletes), changes in testosterone cybernetics may be part of a more advanced adaptive strategy to increase the force production capabilities of muscle. This may occur via potentiation of other hormonal mechanisms in tissue development or by the enhancement of neural factors (39).

Such differences in adaptational strategies appear essential to provide for further gains in performance over the course of a long-term training program. This may reflect the interplay of different neural and hypertrophic factors involved in mediating strength and power changes as training time is extended into years (39, 41).

Growth Hormone

Growth hormone (GH) has been found to be responsive to a variety of exercise stressors, including resistance exercise (11, 24, 35, 40). GH increases in response to breath holding and hyperventilation alone (5), in addition to hypoxia (44). Similar stimulatory mechanisms may operate to varying extents during heavy resistance exercise. It is important to note that not all resistance-exercise protocols demonstrate increases in serum GH concentrations (23).

In an investigation by VanHeldet et al., it was observed that when a light load (28 percent of 7 RM) was used with a high number of repetitions in each set, no changes were observed in the serum concentrations of GH (45). This suggests that in resistance exercise, a threshold exists for intensity (i.e., load) to elicit a significant stimulatory response of the hypothalamic-pituitary axis in response to resistance exercise. It further underscores the concept that various types of resistance-exercise protocols do not alter the peripheral concentrations of GH; this may be due to a combination of too low a resistance or volume of exercise.

Programs (including large muscle group, total-body exercises) that use heavy resistances (5 RM and lower) with longer rest periods (three or more minutes) with moderate or low volume of exercise focus on the nervous system to elicit optimal changes in strength and power with only needed changes in size. Use of such programs provides for only a minimal response of growth hormone to exercise in both men and women (31, 32).

Conversely, programs (again, total-body, including large group exercises) that use moderate resistances (10 RM) and short rest periods (30 seconds to one minute) with high volumes of exercise focus primarily on the optimization of the endocrine system to elicit changes in muscle tissue size, with only the
needed changes in strength and power that 10 RM loads will allow. Here we see a dramatic increase in growth hormone's response to exercise in both men and women. The responses of serum growth hormone to various exercise protocols are shown in Figure 2 from a study by Kraemer et al. (32). In this case, the muscle tissue component of the strength/power and size equation is optimized.

In more advanced resistance-training programs, periodization techniques vary the loads and volume (sets x repetitions x loads) of exercise over the course of training (8, 36, 42, 43). It appears that depending on load and volume of exercise, differential GH responses can occur.

In a recent study, it was demonstrated that GH increases are differentially sensitive to various resistance-exercise protocols (Figure 2) (32). When the intensity used was 10 RM, with high total work (approximately 60,000 joules), and short rest periods (one minute), significant increases were observed in serum concentrations of GH. The most dramatic increases were demonstrated in response to a decrease in rest period (one minute) when the duration of exercise was longer (10 RM versus 5 RM). With such differences related to the exercise configuration (e.g., rest period length) of the exercise session, it appears that greater attention is needed when designing and implementing workouts.

Female Hormonal Response to Heavy Resistance Exercise

Most data examining hormonal responses to resistance exercise and training have used men as subjects. The testosterone hormonal response patterns during growth and development have been credited as being responsible for differences in muscular development and strength in males and females. The higher secretion of adrenal androgens in some females has possibly accounted for the individual variations observed when examining resting concentrations, acute exercise and chronic exercise responses. To date, most studies have shown that females typically do not demonstrate an exercise-induced increase in testosterone after various forms of heavy resistance exercise (7, 22, 31, 46). This may vary with individual females when high adrenal androgen release is possible.

In one report, changes were seen in baseline levels of testosterone compared to inactive controls (2). No changes in women have been demonstrated in serum concentrations of testosterone with training (47). Hakkinen et al. have shown that total and free testosterone changes during strength training were correlated with muscle force production characteristics, but no significant increases were observed (21).

How menstrual phases affect hormonal responses to resistance exercise and training remains unclear. It has been shown that menstrual phase does alter certain hormone concentrations and response to exercise (4). Kraemer et al. found that females during the early follicular phase of the menstrual cycle had significantly higher GH concentrations at rest compared to males (31). Furthermore, when using a heavy resistance-exercise protocol characterized by long rest (three minutes) and heavy loads (5 RM), GH levels were not increased above the resting concentrations. Conversely, when a short rest (one minute) and moderate resistance (10 RM) protocol was used, significant increases in serum GH levels were observed. This suggests that hormonal response patterns to different resistance-exercise routines may not be similar over the course of the menstrual cycle, due to possible alterations in resting levels (31). The possibility of periodizing resistance training over the course of the menstrual cycle remains to be examined. At present, the reduced levels of testosterone and differential resting hormonal levels over the course of the menstrual cycle appear to be the most striking neuroendocrine differences between males and females. How such differences are related to training adaptations, development of muscle tissue and expression of strength and power remains to be demonstrated.

Summary

It appears that growth hormone and testosterone may not always respond in the same way to a resistance exercise workout. When resistance is heavy and rest is long, as characterized by strength/power programs, little change might be expected in circulating levels of growth hormone, but testosterone levels may rise if the amount of muscle tissue mass used in the exercises is great enough. Conversely, if resistance is moderately heavy and of sufficient duration (i.e., 10 RM), and a short rest period is used, increases in growth hormone and testosterone would be expected. The target of the hormones depends on the configuration of exercise stress and the alterations it produces in the nerves and muscle. The amount of muscle mass stimulated, the rest between sets and exercises, and the resistance used are vital factors in eliciting hormonal increases.

Even when using a program dedicated to rehabilitation or body-part exercises, one could theorize the benefits from gaining an increase in anabolic hormones by performing a large muscle group exercise in the training session, causing endocrine glands to release hormones into the blood before starting a session on small muscle groups. Additionally,
the hypertrophy phase of a periodized program might benefit from reductions of rest periods to stimulate tissue changes. Optimal understanding of the physiology of training adaptations and how to optimize the training stimuli will result in better programs.

References


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