Neuromuscular and Hormonal Adaptations to Resistance Training: Implications for Strength Development in Female Athletes

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IT IS WELL ACCEPTED THAT heavy resistance training can result in many physiological adaptations, including increased strength and growth of muscle tissue. Many of the mechanisms contributing to these physiological adaptations are not fully understood, and researchers continue to try and determine the factors that contribute to such responses. Although most research regarding the physiological responses of resistance training has been conducted with male athletes and participants, research over the last 2 decades has begun to examine gender response differences to resistance training stimuli. This review paper will examine general as well as gender differences in both acute neuromuscular and hormonal response to resistance exercise and chronic adaptations to resistance training. This will help dispel myths associated with females and resistance exercise as well as suggest implications for performance enhancement of female athletes through resistance training.

■ Neuromuscular Adaptations to Resistance Exercise

Resistance training stimulates many physiological mechanisms in the human body. Two primary factors contributing to increased muscle strength are both neural and muscular adaptations. Physiological responses to resistance training seem to be mediated by prior training and genetic potential as well as by the type of resistance training protocol (2, 10, 20, 23, 28, 34).

Neural factors facilitate increases in strength through more efficient motor unit recruitment, increased motor unit synchronization and activation, and inhibition of protective mechanisms of the muscle (10, 20, 42). Neural adaptations are particularly enhanced in the early phases of training, when individuals may experience significant increases in strength without increased muscle size (14, 15, 20, 23, 42).

As training progresses, muscle hypertrophy plays an increasing role in strength development. Muscle hypertrophy occurs from resistance training due to protein remodeling in the muscle cells, resulting in increased cross-sectional size of individual fibers. It is now well accepted in the field of exercise physiology that the majority of muscle hypertrophy in adult mammals is due to this increase in muscle cell size rather than to an increase in the number of fibers, or hyperplasia (6, 10, 44).

Hypertrophy due to heavy resistance training does occur in both slow-twitch and fast-twitch muscle fiber types; however, the greatest amount of muscle hypertrophy occurs in the fast-twitch Type II fibers (4, 26, 37, 40, 46). Muscle fiber type conversions occur as a result of resistance
training as well. Heavy resistance training stimulates the conversion of fast-twitch Type IIb fibers to Type Ila or other Ila fiber subtypes (4, 23, 26, 46). Any transformation of Type I fibers to Type II appears less probable and has not been demonstrated (20, 46). The reduction in Type IIb fibers from high-intensity strength training may be attributable to the recruitment of high-threshold motor units with heavy resistance training (20, 26). The changes in muscle fibers as a result of heavy resistance training begin to take place within just a few workouts (42), although noticeable changes in cross-sectional fiber area tend to appear after more than 8 weeks of training (10, 17, 24, 42).

Program variables, such as intensity and volume, appear to be related to degree of muscle strength and hypertrophy gains (10, 17, 27, 28). Training programs incorporating multiple sets of 8–12 repetition maximum (RM) loads and relatively short rest periods have been suggested for developing muscle hypertrophy because this promotes tension stimulus of long duration (4, 10, 33). However, although muscle hypertrophy contributes to maximal strength, increased muscle size may not necessarily always result in increased maximal strength (11).

Studies have shown that increases in muscle hypertrophy can plateau in trained individuals. A study of competitive weightlifters revealed that, although strength increased over 2 years of training, there were minimal changes in muscle size (11). This suggests that other factors may be of greater contribution to the strength development of advanced resistance-trained athletes, such as neural and hormonal responses to training (11).

### Acute Hormonal Response to Resistance Exercise

Resistance exercise provides an acute stimulus to the neural system, which then results in a stimulation of the endocrine glands to secrete hormones. This close link between the neurological and endocrine systems is often referred to as the neuroendocrine system. The neuroendocrine system is very complex, and numerous interactions occur among hormones influenced by genetic predisposition, training status and protocol, nutritional status, stress, and sleep (23). The amount of hormone response depends on the amount of muscle tissue and amount of muscle repair and remodeling stimulated by the resistance training (19).

The physiological stress of resistance training as well as the secretion of anabolic and catabolic hormones can lead to the potential for adaptations of the skeletal muscle tissue; however, few studies actually provide evidence for chronic adaptations.

### Testosterone

Testosterone (TST), the male sex hormone, has long been thought of as the main reason for muscle size differences in men and women. Through both direct interaction with skeletal muscle and indirect interaction with other hormones and the neurons innervating muscle. TST has been shown to increase the rate of protein synthesis as well as to inhibit protein degradation (an antianabolic effect) (6, 19). In males, acute serum TST concentration has been increased through resistance training with large-muscle group exercises, heavy resistance (85–95% of 1RM), and moderate to high volumes of exercise (18, 19, 24).

Prior evidence has suggested that serum TST levels may not be chronically affected by resistance training (12, 18, 37). Yet Staron et al. (42) demonstrated that resting TST levels were increased in previously untrained male subjects, and Kraemer et al. (28) reported similar results after 8 weeks of training with both male and female subjects. In addition, Staron et al. (42) found significant correlations between the resting TST levels and fiber types (increased Ila, decreased IIb). Hakkinen et al. (11) reported that elite weightlifters had increases in resting TST levels over 2 years of training as well as increases in other male sex hormones, luteinizing hormone, and follicle-stimulating hormone. Although the strength of these elite athletes increased over the 2 years, there were some fluctuations, which corresponded to the observed fluctuations in TST levels (11).

Research has also examined free TST versus TST bound to a protein, such as sex hormone-binding globulin (SHBG) (19). Free TST is the most anabolically active form of TST (47). Studies have found that a higher TST/SHBG ratio (also termed free androgen index) is related to muscle hypertrophy in untrained subjects (12, 14). Other research has revealed that a higher resting TST/SHBG ratio is related to maximal strength in elite weightlifters, and fluctuations in this ratio closely followed fluctuations in performance (11). Another study of trained males reported that increases in strength correlated with increased TST/SHBG ratios during the final 4 weeks of a 24-week training period; decreases in strength over 4 weeks of detraining were also correlated with decreases in the TST/SHBG ratios (13).
Growth Hormone and Insulin-Like Growth Factors

Secreted from the anterior pituitary gland, anabolic growth hormone (GH) increases muscle protein synthesis and may decrease muscle protein breakdown, similar to testosterone (17, 19). Growth hormone contributes to the synthesis of insulin-like growth factors (IGFs), in particular IGF-I. Both GH and IGF-I stimulate the growth of lean muscle tissue (17, 19). Various forms of GH exist, although the role of varying forms in muscle tissue growth is still unclear. The 22-kDa GH is the most commonly measured isoform (19, 44). Kraemer et al. (28) hypothesize that the type of GH produced may be important to resistance training adaptations and the stimulation of other hormones, such as IGF-I.

Training protocols that utilize moderate- to high-intensity, high-volume, large-muscle groups and shorter rest periods have been shown to increase acute postexercise serum GH concentrations (22, 24, 28, 33, 37, 44). Such types of exercise protocols increase blood lactate and hydrogen ion concentration through glycolytic metabolism, which is believed to stimulate the GH response (19, 28, 37, 44). In their 12-week study of college males, McCall et al. (32) found significant correlations between acute exercise-induced GH increases and relative degree of hypertrophy in Type I and Type II fibers. Although these correlations are not evidence that GH causes muscle hypertrophy, the relationship could be indicative of the influence that repeated acute exercise-induced elevations in GH have on cellular adaptations in the trained muscle (32). The majority of research has not found chronic adaptations in resting levels of GH as a result of resistance training (28, 32, 43).

Insulin

Muscle hypertrophy is dependent on the net difference between protein synthesis and degradation caused by exercise. MacDougall et al. (31) demonstrated that, following heavy resistance exercise, muscle protein synthesis is elevated by an average of 50% at 4 hours and 109% at 24 hours and then falls to 14% at 36 hours. However, protein synthesis is also accompanied by protein degradation, likely due to the mechanical damage to contractile tissue during heavy resistance exercise (31). Insulin, from the beta cells of the pancreas, has an anabolic effect on muscle. Immediately after exercise, insulin-stimulated amino acid uptake is enhanced (3). It is hypothesized that insulin may act by increasing muscle protein synthesis, decreasing muscle protein breakdown, or a combination of both (8, 17).

Studies have shown that postexercise carbohydrate and protein ingestion increases both insulin and growth hormone concentrations. A study by Roy et al. (39) indicated that postexercise carbohydrate supplementation resulted in increased serum insulin concentrations, stimulated muscle protein synthesis rates, and reduced markers of muscle protein breakdown. Researchers suggest that inducing insulin and other hormonal responses through caloric, protein, and carbohydrate supplementation will enhance anabolic processes stimulated by resistance training (8, 17, 30, 39).

Interestingly, it seems that there is an inverse relationship between acute insulin and testosterone concentrations due to resistance training (8, 30). In a study of supplementation during consecutive days of heavy resistance exercise in males, insulin concentrations were highest when testosterone levels were lowest, and vice versa (30). However, TST/SHGB levels remained the same between supplementation and placebo groups, suggesting that free testosterone levels remained stable despite lowered total testosterone concentrations (30). Further research on this testosterone–insulin relationship is needed.

Cortisol

Cortisol, a primary glucocorticoid from the adrenal cortex, is considered a catabolic hormone because it inhibits muscle protein synthesis and increases the level of enzymes that break down protein. As blood glucose levels drop due to the stress of resistance exercise, cortisol allows for the breakdown of amino acids in muscle to maintain blood glucose homeostasis (6). These acute increases in cortisol occur as a result of the stress of exercise, contributing to the tissue remodeling process (22, 37).

In many studies, previously untrained individuals have demonstrated chronic decreases in resting cortisol concentrations after programs of heavy resistance training (15, 27, 28, 43). In one study, a significant decrease in resting cortisol levels was demonstrated in both previously untrained men and women who performed 8 weeks of high-intensity (6–12 RM) resistance training (27). A study of trained male subjects indicates that a decrease in resting cortisol levels can be demonstrated by trained individuals as well (13).

A decrease in resting cortisol levels could increase the potential for the hypertrophy of Type I muscle fibers. These slow-twitch fibers rely on a reduction in protein
Catecholamines

Secreted by the adrenal medulla, catecholamines (epinephrine, norepinephrine, and dopamine) are probably one of the first endocrine responses to acute physiological stress such as resistance exercise. Although the specific role of catecholamines in physiological adaptations to resistance training is unclear, they do act to stimulate and regulate other anabolic hormones (19). Increases in catecholamine levels due to resistance training seem to be related to the amount of muscle mass activated, the amount of force produced by the muscle, and the length of the rest period (18). In a study by Kraemer et al. (26), mean epinephrine, norepinephrine, and dopamine levels all significantly increased postexercise when the exercise routine utilized a heavy resistance training protocol and very short rest periods. However, the effects of catecholamines on muscle hypertrophy are unknown and should be a topic of future study.

Hormonal Response by Gender and Training Protocol

It seems that observed differences between genders in acute hormonal responses to resistance exercise are related to the difference in resting hormone concentrations. One of the most noticeable differences between the genders is in resting and exercise testosterone levels. Males consistently demonstrate higher concentrations of testosterone both pre- and posttraining compared with females (15, 24, 28, 42, 48). In general, females have shown a lack of testosterone responsiveness to various resistance exercise protocols (10, 22, 24, 28, 42, 48). In a study by Hakkinen et al. (14), women with higher testosterone/SHBG ratios experienced the greatest amount of muscle hypertrophy over 8 weeks of training, suggesting that amount of free testosterone is indicative of potential for muscle strength and hypertrophy in women. But recent studies indicate that anabolic hormones other than testosterone may potentially contribute to hypertrophic training adaptations in women (10, 22, 24, 37, 44).

As with males, type of exercise protocol seems to affect acute GH response in women. In a study comparing responses by training protocol and gender, females who participated in a 10RM, 1-minute rest, multiple set protocol increased acute levels of GH significantly, whereas females who utilized a 5RM, 3 minute rest, multiple set protocol did not (24). Males increased their acute GH response utilizing both protocols, although significantly more with the shorter rest protocol. Females had significantly higher resting-level GH compared with males. It is believed that this greater resting level of GH in females is related to estrogen levels, although further research is necessary (22, 24, 40, 44). The importance of increased GH concentrations in females at rest as well as in response to acute resistance exercise remains to be determined.

In a second study by Kraemer et al. (22), program variables of heavy resistance load and short rest period length were again seen to be important stimuli for GH as well as cortisol levels in women. Female subjects randomly performed 2 of 6 heavy resistance training protocols on separate days: 3 strength workouts and 3 workouts specific to increasing muscle hypertrophy. The 3 strength workouts consisted of 5RM, 3 minute rest (S5/3); 5RM, 1 minute rest (S5/1); or 10RM, 3 minute rest (S10/3) protocols. The 3 hypertrophy workouts consisted of 10RM, 1 minute rest (H10/1); 10RM, 3 minute rest (H10/3); or 5RM, 1 minute rest (H5/1) protocols. Blood concentrations of various hormones and metabolic indicators were taken at rest, midway through the workout, and at regular intervals up to 2 hours postworkout. Results indicated no change in serum testosterone or total IGF-I, although this was not a surprising result for IGF-I because levels often do not peak.
Although it has been shown that acute growth hormone response is increased by moderately heavy resistance, high volume, and short rest resistance protocols in females, these studies have only been conducted on women who were in the follicular phase of menstruation. The effect of various resistance training protocols on hormone release in all phases of the menstrual cycle, the role that estrogen plays in GH release, and the potential influence of GH release on chronic training adaptations in women are necessary topics for further study.

**Hypertrophic Response by Gender and Training Protocol**

As stated earlier, many factors can come into play to influence muscle hypertrophy: genetics, training status, exercise protocol, nutrition, and possibly hormone response. One genetic difference that seems to occur between the genders is in muscle fiber size as well as fast-twitch to slow-twitch muscle fiber ratio. Studies have shown that males have increased muscle fiber size compared with females (4, 5, 35, 41) as well as a greater ratio of fast-twitch to slow-twitch fiber area (4, 10, 36, 41, 42). Females have more intramuscular fat and connective tissue per cross-section of muscle area than males do (10, 41).

Women do have decreased absolute strength compared with the absolute 1RM of men. When expressed as strength relative to lean body mass or muscle cross-sectional area, the differences in strength between the genders often decrease or are even eliminated (4, 7, 35, 42). When compared relative to lean body mass, some studies indicate that lower-body strength is still less in women than in men (38, 40, 45), while some research suggests that upper-body strength is still significantly lower in females (5, 16, 35, 45). Although Miller et al. (35) found significant gender differences in strength relative to lean body mass, these differences were eliminated when compared with muscle cross-sectional area. Women had 45, 41, 30, and 25% smaller muscle cross-sectional areas for biceps brachii, total elbow flexors, vastus lateralis, and total knee extensors, respectively, which accounted for strength differences (35).

In a study by Bishop et al. (5), although most gender differences in strength were eliminated when adjusted for lean body mass and muscle cross-sectional area, upper-body strength measures were not. Miller et al. (35) stated that greater gender discrepancy in upper-body strength can probably be attributed to the lower proportion of lean tissue in the upper body of women. Current research continues to debate the best method of comparing gender differences in strength; some research indicates that true body-size adjusted strength is not accurately assessed by simple ratio expressions (45) and should be a topic of future study.

It does seem that relative strength discrepancy between genders, if it indeed exists, could be diminished with training (42, 25). In a study by Staron et al. (42), pretraining strength relative to lean body mass values for females in the squat, leg press, and leg extension were 68, 77, and 67%, respectively, of males. After 8 weeks of heavy resistance training, the females increased their relative strength values to 88, 107, and 89%, respectively, of the males. In another study, absolute gender differences in strength were decreased for trained swimmers compared with untrained in-
dividuals for both upper- and lower-body measures (5).

Males have demonstrated a greater rate of muscle force development, as indicated by quicker speed to maximal force and subsequent muscle fatigue over 30 seconds in isometric leg extension exercise (40). However, when this rate of force development was examined on a relative scale based on percent of maximal force, the difference between males and females was not as pronounced (40). Slower time to reach an absolute percent of muscle force is likely explained by lower absolute strength in women.

As indicated, there is no difference between genders in relative strength and hypertrophy gains (percent increases) from resistance training programs (1, 9, 10, 42, 43). A recent study found that, over 12 weeks of heavy resistance training, the mean relative increases in knee extension and chest press strength were similar for previously untrained men and women, as were mean increases in muscle hypertrophy (1). However, due to the possible interaction of many factors such as hormone response and muscle fiber size, females do not achieve the same amount of absolute hypertrophy as males.

Many females avoid heavy resistance training out of fear of it resulting in large, bulky muscles. But most females do not increase (or may even decrease) body circumference areas with resistance training due to a decrease in body fat accompanied by the increase in muscle mass. In a study by Staron et al. (43), women participated in a 20-week heavy resistance training program for the lower body. Poststudy testing showed that participants had a decrease in body fat and an increase in muscle tissue, with no overall change in thigh circumference (43). As stated earlier, large amounts of muscle hypertrophy require a genetic predisposition, large training volume, positive caloric and proper nutrient balances, among other factors. So although some elite female body builders have demonstrated extreme muscle development, the average woman can rest assured in being able to increase strength and power without large increases in circumference area.

**Implications for Training**

As the research has demonstrated, both males and females seem to respond equally to relative increases in strength and hypertrophy from resistance training. Optimal training for both men and women will be specific to their training objectives, and, for all athletes, this will include training designated for muscular strength, endurance, power, and hypertrophy. Few studies have actually examined the influence of long-term resistance training on women, and only 1 study has examined performance adaptations as related to type of resistance training protocol. In a recent study by Kraemer et al. (25), military women who engaged in various types of strength training resulted in improved performance and adaptations specific to the type of training performed (strength/power or strength/hypertrophy resistance protocols). Regardless of type of training protocol, women who engaged in total-body and upper-body resistance training improved performances in occupational tasks, especially in those tasks requiring upper-body strength (25).

As discussed earlier, some research has found that females do have less upper-body strength relative to lean body mass or muscle cross-sectional area compared with males (5, 16, 35). This suggests that female athletes requiring a strong and powerful upper body for their sport may need a greater percentage of training time devoted to the specific development of upper-body strength (10). In particular, athletes in upper-body dominated sports such as softball, swimming, Olympic and power lifting, and throwing events could potentially benefit from increased training time devoted to such development.

Although increased hypertrophy has not always resulted in improvements in strength performance (11), some research has found that the lower absolute strength of women is correlated with less total muscle mass and cross-sectional muscle size compared with men (5, 25, 35). Furthermore, it has been hypothesized that trained women may have greater acute growth hormone response to resistance training due to increased muscle mass as well as motor unit recruitment compared with untrained women (44). This suggests that additional training time devoted to hypertrophy phases of training in female athletes may increase acute hormone response to exercise and stimulate an increase in lean body mass, which could potentially further stimulate acute hormone response. An increase in muscle mass could then contribute, through varied cycles of training, to greater development of muscle strength and power. Devoting a greater amount of off-season training to higher volume, shorter rest-period training, especially in sports requiring upper-body strength, may stimulate muscle development in female athletes.

As the research has demonstrated, although both genders experience muscle hypertrophy resulting from training, females will
not experience the same absolute degree of strength and hypertrophy. Many factors may contribute to female strength and hypertrophy, including muscle fiber size, Type I to Type II fiber ratios, repeated acute hormonal response to resistance exercise, and nutritional status. As we continue to try and understand the mechanisms that contribute to muscle hypertrophy and strength and gender differences in such mechanisms, further research into the role of acute hormonal responses and chronic adaptations from training is certainly necessary, especially in women. Until then, strength and conditioning coaches should continue to vary the training of women, as with men, as the sport demands, with a suggested emphasis on off-season hypertrophy training for upper-body dominant sports.

References


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