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Eccentric Exercise Testing and Training

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Introduction

Some researchers and practitioners have touted the benefits of including eccentric exercise in strength training programs. However, others have challenged its use because they believe that eccentric actions are dangerous and lead to injuries. Much of the controversy may be based on a lack of understanding of the physiology of eccentric actions. This review will present data concerning eccentric exercise in strength training, the physiological characteristics of eccentric exercise, and the possible stimulus for strength development. Also a discussion of strength needs for extended exposure to microgravity will be presented.

Not only is the use of eccentric exercise controversial, but the name itself is fraught with problems. The correct pronunciation is with a hard "c" so that the word sounds like *ekscentric* [6]. The confusion in pronunciation may have been prevented if the spelling that Asmussen used in 1953, *excentric*, had been adopted [30]. Another problem concerns the expressions used to describe eccentric exercise. Commonly used expressions are *negatives*, *eccentric contractions*, *lengthening contractions*, *resisted muscle lengthenings*, *muscle lengthening actions*, and *eccentric actions*. Some of these terms are cumbersome (i.e., resisted muscle lengthenings), one is slang (negatives), and another is an oxymoron (lengthening contractions). Only *eccentric action* is appropriate and adoption of this term has been recommended by Cavanagh [5].

Despite the controversy that surrounds eccentric exercise, it is important to note that these types of actions play an integral role in normal daily activities. Eccentric actions are used during most forms of movement; for example, in walking when the foot touches the ground and the center of mass is decelerated and in lowering objects, such as placing a bag of groceries in the car.

Training Studies

The effects of training with eccentric actions versus other types of actions has received a moderate amount of attention over the last 25 years [1, 7, 27]. Several factors need to be considered when examining these training studies. First, there is a problem in equating workloads. Eccentric actions can produce more tension than concentric or isometric actions. Thus, the workload may be set relative to the maximal tension that could be generated for each modality (i.e., concentric, eccentric, isometric), or the workload may be set at the same value for each of the modalities. Second, the method of strength assessment differs among studies. For example, some investigators measured isometric strength pre and posttraining regardless of the mode of actions used in the training exercise (i.e., eccentric, concentric, isometric), while others measured the same type of actions that were used in the training. Studies also differ on the muscle groups examined, as well as the duration and the intensity of the training regimens. However, despite the differences among studies, the results of the investigations are markedly consistent.

Eccentric vs. Concentric

Mannheimer [21] investigated strength gains in 26 patients at a center for neuropsychiatric disorders. Subjects participated in a 1-month training program that consisted of either eccentric-only or concentric-only actions of the elbow flexors. The exercises were performed on a specially designed variable muscle tester with shock absorbers to provide resistance. Pre- and poststrength testing was specific to the exercise performed. Although both training regimens produced strength gain, there was no significant difference between them.

In a 6-week training program, six medical students performed a specially devised training program to include various exercises [15]. Some of these exercises were performed using concentric actions and others performed using eccentric actions. No difference in dynamic strength gain could be ascertained between the two exercise regimens.

Johnson [13] and Johnson *et al.* [14] examined strength gains that were achieved by training one limb with eccentric actions and the other with concentric actions. In the 1972 study [13], nine subjects trained for 8 weeks at 80 percent of concentric one repetition maximum (1RM). There was no significant difference in strength gain between the training regimens. In the 1976 study [14] the workloads were reset so that 80 percent 1RM was used for the concentric regimen and 120 percent 1RM (concentric 1RM) was used for the eccentric regimen. Although strength gains were found for arm curls, arm presses, knee flexions and extensions, there was no significant difference in strength gain between the exercise regimens.

Only Komi and Buskirk [19] have found that eccentric exercise produced greater strength gain than concentric exercise. In this study, three groups of subjects (n=10 per group) trained for 7 weeks on an electric dynamometer using the forearm flexor muscles. The groups performed either maximal eccentric, concentric, or isometric actions. The eccentric training regimen resulted in the largest strength gains for each of the testing modalities (i.e., concentric, isometric and eccentric). The major difference between the Komi and Buskirk [19] study and previously described studies is that Komi and Buskirk used maximal eccentric actions in the training program.

In a recent study, Jones and Rutherford [16] examined isometric strength of the knee extensors and muscle cross sectional area of the mid thigh before and after 12 weeks of eccentric exercise with one leg and concentric exercise with the other leg. The work load was set at 80 percent 1RM (concentric or eccentric) for the six subjects tested. The forces generated during the eccentric training were 45 percent higher than forces generated during the concentric training. The results showed that both eccentric and concentric training increased isometric strength (11 percent and 15 percent, respectively) but there was no significant difference between the two training regimens. There was a similar increase (5 percent) in muscle cross sectional area (determined from computerized tomography scans) for the eccentric and concentric training. Also found was a small, but significant increase in the radiological density of the muscle for both exercise regimens. This increase may result from an increased packing of the myofibrils, an increase in connective tissue, or a decrease in fat content of the muscle [16].

Eccentric vs. Isometric

Bonde Petersen [3] had subjects perform either ten-maximal isometric actions or ten-maximal eccentric actions (elbow flexors) per session for 36 sessions over 2 months. The isometric exercise training regimen produced a small, but not significant, increase in isometric strength, and the eccentric actions had no effect on isometric strength.

The other study to compare the effects of isometric and eccentric training regimens did find strength gains and reported no difference between the training regimens [20]. Laycoe and Martiniuk [20] had two groups of 15 subjects perform either three-maximal eccentric actions or three-maximal isometric actions of the knee extensors for 6 weeks. Eccentric and isometric trained groups showed a significant increase in isometric strength (17.0 percent and 17.4 percent, respectively). The eccentric group, however, improved 41 percent in eccentric strength. Eccentric strength was not measured for the isometric trained group.

Hybrid Exercise Programs

Hakkinen and Komi [11] examined the effect of training with only concentric exercise compared with combinations of concentric and eccentric exercise. Three groups were studied: Group 1 performed concentric squatting exercise, Group 2 performed the same concentric exercise with some additional eccentric, and Group 3 performed predominantly eccentric squatting actions plus some concentric actions. Squatting ability after 12 weeks of training showed greater improvement for the groups that performed the combination exercise modalities compared with the group that performed the concentric training. There was no difference in improvement between Groups 1 and 2.

Slobodyan [29] and Pletnev [26] also examined the effectiveness of hybrid training programs in strength gain. Slobodyan studied three groups who trained with a series of standard exercises over 3 months. The groups differed in the following manner: Group 1 performed 100 percent concentric exercise; Group 2 performed 75 percent concentric exercise, 15 percent eccentric exercise, and 10 percent isometric exercise; and Group 3 performed 50 percent concentric, 30 percent eccentric, and 20 percent isometric exercise. On all tests, Group 3 showed the greatest strength gains. Pletnev [26] compared strength gains in four groups after 3 months of training: one trained isometrically, one eccentrically, one concentrically, and one used a combination of the three modalities. Overall the group performing the hybrid program demonstrated the greatest gains in strength.

Characteristics of Eccentric Exercise

Lower Oxygen Cost

In laboratory testing of eccentric and concentric muscle actions, subjects will consistently report that exercises with eccentric actions are easier to perform than exercises with concentric actions. Rasch, in his review of eccentric exercise [27], stated that when using oxygen consumption as the criterion measure, "muscles are able to produce tension three to nine times more cheaply when they are doing negative work than when they are doing positive work."

Several studies have shown that the rate of oxygen uptake by subjects who were performing concentric only exercise was greater than oxygen uptake for subjects performing eccentric exercise [27, 30]. Early studies have suggested that the lower oxygen cost of eccentric exercise was due to a smaller number of muscle fibers being recruited during eccentric actions. However, Bigland-Ritchie and Woods [2] found that motor unit recruitment could only partially explain the difference in oxygen cost between concentric and eccentric actions.

Bigland-Ritchie and Wood [2] examined integrated EMG (IEMG) of the vastus lateralis muscles and oxygen uptake during concentric and eccentric cycle ergometry exercise. The pedaling rate was set at 50 rev/min with resistances ranging from 2.5 to 15 kg. Work rates did not exceed 75 percent of the subjects' $\dot{V}O_{2max}$. When the slope of IEMG/work-rate for concentric exercise was expressed as a ratio of the slope of IEMG/work-rate for eccentric exercise the value was found to be 1.96. However, a considerably larger value (6.34) was obtained when the slope of $\dot{V}O_2$/work-rate for concentric exercise was expressed as a ratio of the slope of $\dot{V}O_2$/work-rate for eccentric exercise. These data demonstrate that only part of the lower oxygen cost during eccentric exercise could be attributed to less fiber activity. Experiments with isolated muscles that were electrically stimulated have supported this conclusion [30].

Greater Tension

It is common knowledge among those involved in strength testing and training, that individuals can lower more weight than they can lift. Thus, during an eccentric action the muscle can produce more tension than during a concentric action. The force velocity relationship maintains that as the velocity of contraction decreases, the force increases, such that during *negative* velocity contractions (i.e., eccentric actions) the force continues to increase until a certain point is reached.

Stauber in his excellent review of eccentric exercise [30] provides one explanation for the ability of muscle to produce greater tension during eccentric muscle actions. In a resting state, actin and myosin are not bound and the myosin head is in a state of activation due to the hydrolysis of ATP. The myosin head in this state is referred to as *preenergized.* During concentric exercise, myosin heads bind to actin, cross-bridges are formed, and the cycling of these cross-bridges produces tension and shortening. After each cycle of cross-bridge formation, the myosin head is detached from the actin and is recharged with another ATP. In this manner the "potential energy stored in the preenergized myosin becomes transformed into the mechanical events of cross-bridge action (tension or shortening)" [30]. During eccentric actions, the cross-bridge is forcibly pulled backward before energy can be transformed. Stauber [30] states "Each of these attachment-separation reactions produces a recorded tension (resistance to stretch) by the muscle but with no apparent energy consumption because the cross-bridge has not cycled but continues to remain in the high-energy form." To a given point, the faster the velocity during eccentric actions, the less likely a cross-bridge will cycle and the more tension can be produced. Likewise as the velocity decreases, more cross-bridges can cycle and the tension is lower.

Muscle Damage

Well known to athletes, coaches, and exercise scientists is the muscle soreness that develops 24 to 48 hours after exercises that have a large eccentric component [9]. Soreness is considered to indicate that some damage has been incurred in the exercised muscle [9]. In recent years, several studies have appeared in the literature with titles that include such phrases as *exercise-induced muscle damage.* These studies have used eccentric muscle actions as a model to study muscle damage and recovery.

Unfortunately (and undeservedly), these titles may have given eccentric exercise a *bad name.* The damage that is induced by these exercises is completely repairable in a short amount of time. In addition to being repairable, the damage also results in an adaptation in the muscle making it more resistant to damage from subsequent strenuous exercise. In other words, the muscle is designed to deal with effects of eccentric exercise. A more comprehensive discussion of muscle damage and eccentric exercise can be found in two recent review papers [9, 30].

Friden [10] and Newham *et al.* [25] have documented ultrastructural changes in muscle biopsy samples taken from subjects who had performed strenuous eccentric exercise. Both studies noted disruption of the normal myofibrillar arrangement. In normal muscle fibers the Z lines of adjacent myofibrils are in register with one another. After eccentric exercise the Z lines appear to lose their integrity, such that the lines broaden and show a *streaming* pattern. In biopsy samples taken 6 to 7 days after eccentric exercise, the fibers were repaired and appeared essentially normal [9].

Many studies have documented an increase in the appearance of muscle proteins, particularly creatine kinase (CK), in the blood after eccentric exercise [8, 9, 23, 24]. Increased levels of these proteins in the blood has been taken as evidence of muscle fiber membrane disruption. Because CK is a large molecular weight 12 protein, the membrane must be disrupted for release to occur. Also the size of the protein necessitates its entry into the lymph (rather than capillaries) prior to entering the blood via the thoracic duct. Figure 1 shows the pattern of increase in CK activity in blood after high-force eccentric exercise of the forearm flexor muscles. Noteworthy is the 48-hour delay in the increase of CK. Other studies, where less strenuous forms of eccentric actions have been used (Figure 1), have reported a smaller increase in CK in the blood and a shorter delay, generally about 6 to 12 hours after exercise [4, 9]. This 6 to 12-hour delay may be related to the time it takes for CK to travel through the lymph before entering the blood. Presently there is no clear explanation for the long delay of 48 hours. Either there is a delayed release from the muscle or there is an inability of this large protein to enter the lymph or be transported by the lymph. High-force eccentric actions can produce more muscle swelling than less strenuous eccentric exercise (downhill running). Edema around the muscle may retard the entry of large molecular weight proteins into the lymph or retard the transport.

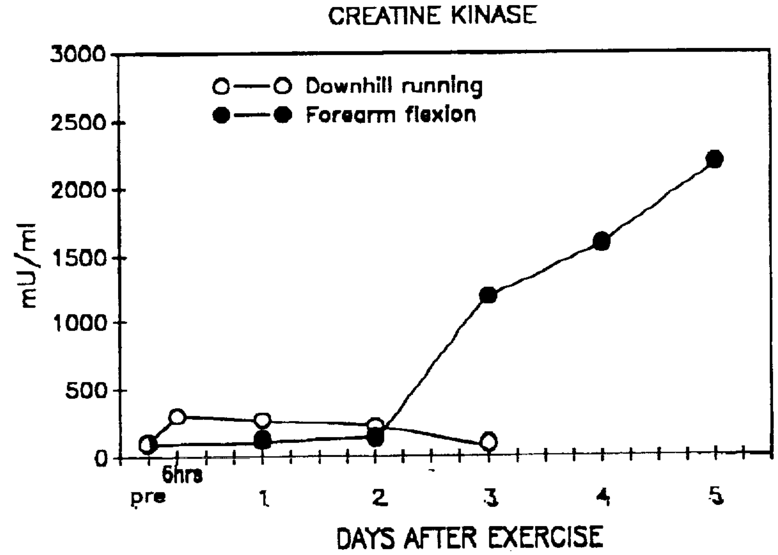

Figure 1. *Creatine kinase activity in the blood before and 5 days after a downhill running exercise (open circles) and high-force eccentric forearm flexion exercise (closed circles). Data modified from Byrnes et al. [4] and Clarkson and Tremblay [8].*

Muscle soreness develops about 24 hours after eccentric exercise, reaches peak values about 48 hours after, and gradually dissipates by 5 to 10 days after exercise (Figure 2). Some investigators have suggested that swelling and edema produce the sensation of soreness. In our studies we have noted swelling long after soreness has dissipated [9]. Soreness may also be the result of chemical irritants, such as histamine and bradykinins, generated by the damaged tissue.

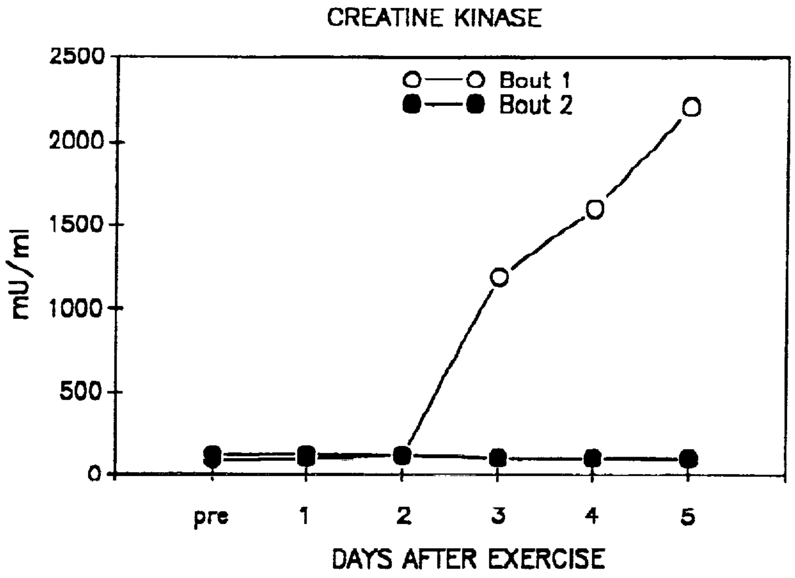

Figure 2. *Muscle soreness of the forearm flexor muscles before (pre) and 5 days after a high-force eccentric forearm flexion exercise. Data modified from Clarkson and Tremblay [8]. Bout 1 (open circles) depicts changes following 70 maximal eccentric actions with one arm. With the other arm subjects performed 24-maximal eccentric actions and 2 weeks later performed 70-maximal eccentric actions; Bout 2 (closed circles) shows data from these latter 70-maximal eccentric actions. For more detailed explanation of the study see reference 8.*

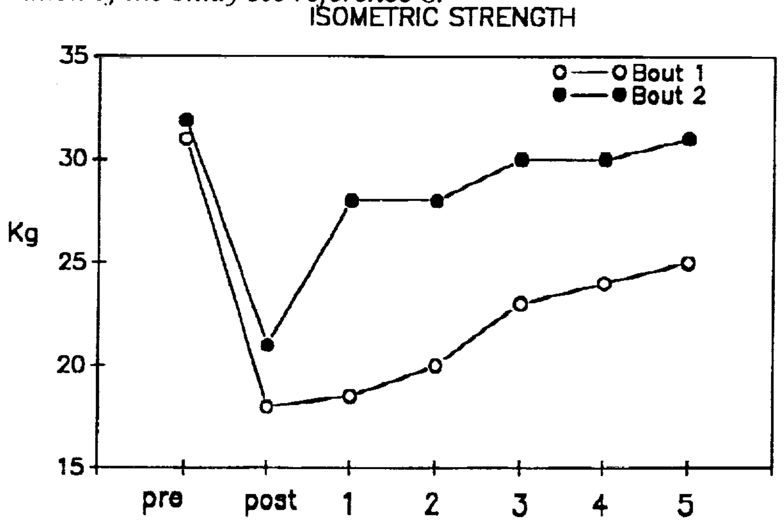

Figure 3. *Isometric strength of the forearm flexor muscles before (pre), immediately after (post), and 5 days after a high-force eccentric forearm flexion exercise. Data modified from Clarkson and Tremblay [8]. See legend for Figure 2.*

Also associated with eccentric actions is strength loss and decreased range of motion in the days following the eccentric exercise. Clarkson and Tremblay [8] showed that isometric strength was decreased by about 50 percent immediately after high-force eccentric exercise and gradually returned toward baseline (Figure 3).

Range of motion was shown to decrease immediately after the exercise, further decreased at 2 days after exercise, and then returned toward baseline [8] (Figure 4).

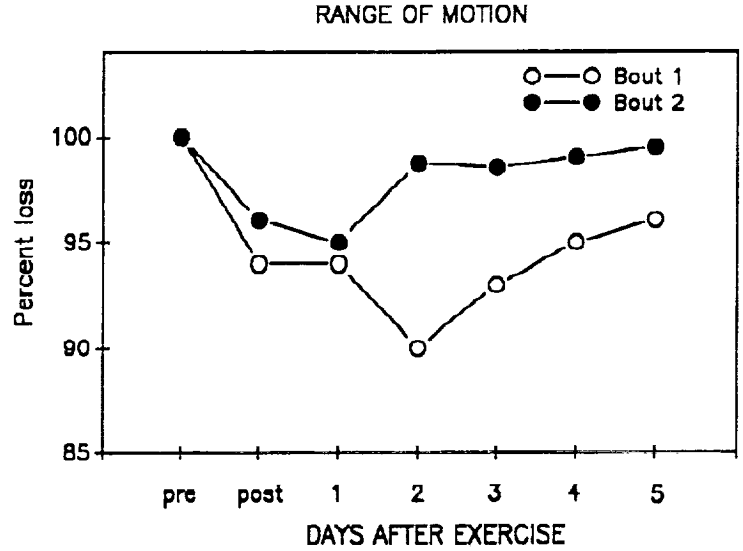

Figure 4. *Range of motion about the elbow before (pre), immediately after (post), and 5 days after a high-force eccentric forearm flexion exercise. Range of motion is expressed as a percentage of preexercise range. Data modified from Clarkson and Tremblay [8]. See legend for Figure 2.*

Within 7 to 10 days after performance of high-force eccentric exercise, muscle function is fully recovered [9]. Moreover, during the recovery process, an adaptation or training effect takes place. When subjects perform a subsequent bout of high-force eccentric exercise, they are able to perform more work [8, 9, 23]. Also, less damage is incurred from the second exercise [8, 9, 23]. In Figure 2, less soreness develops after Bout 2 compared with the first bout, strength and range of motion are restored more quickly after the second bout (Figures 3 and 4, respectively), and most noteworthy, there is no release of CK into the blood after Bout 2 (Figure 5). Thus, performance of the first eccentric exercise produced an adaptation (or rapid training effect) in the muscle such that it was more resistant to damage from a subsequent bout of strenuous exercise. This training effect can also be elicited when the first bout of eccentric exercise produces little muscle damage [8]. There is evidence to suggest that the training effect can last 6 weeks or longer [9].

It is important to note that the adaptation effect described above cannot be elicited by concentric training [28]. Sforzo and Lamb [28] investigated the effects of concentric training and eccentric training (at the same absolute workload) in two groups of subjects. After 2 weeks of training, these subjects performed a strenuous bout of exercise that incorporated concentric and eccentric actions (con-ecc). The concentric trained group developed considerable soreness after the strenuous bout of con-ecc exercise but the eccentric trained groups did not. This finding is particularly noteworthy since the absolute workloads were the same thereby making the training regimen more strenuous for the concentric trained group.

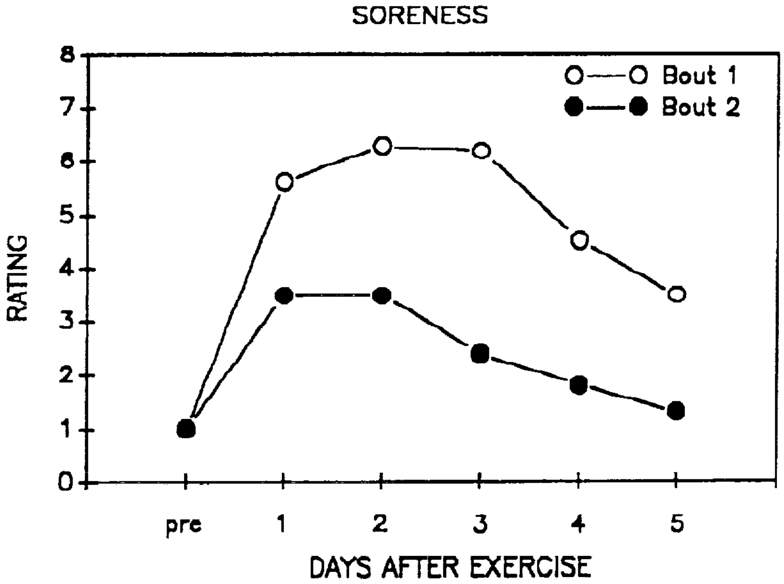

Figure 5. *Creatine kinase activity in the blood before (pre) and 5 days after a high-force eccentric forearm flexion exercise. Data modified from Clarkson and Tremblay (8). See legend for Figure 2.*

In our laboratory we have tested over 300 subjects who have performed high-force eccentric exercise and we have never had an injury occur. These subjects included a sample of persons between the ages of 60 and 70 years. Other laboratories in this country and in England have also used high-force eccentric exercise and have not had an injury (either reported in the literature or personal communication).

One physiological explanation for a lack of injury with eccentric actions is that a protective reflex serves to prevent the muscle from generating more tension than it can accommodate safely. Evidence for such a reflex is indirect. The ratio of eccentric force to concentric force is greater for isolated muscle compared with intact human muscle [30]. Stauber [30] suggested that this discrepancy can be explained as a function of central nervous system (CNS) actions in intact muscle. Also, when muscle is electrically stimulated during eccentric actions, the same high-force can be achieved as in isolated muscle [30]. Thus, the development of the full force capability during normal eccentric actions may be prevented by CNS intervention thereby protecting the muscle from injury. A similar mechanism has also been suggested for other forms of muscle actions. Stauber [30] proposes that only when these protective reflexes are fatigued will myotendinous tearing occur.

In summary, high-force eccentric exercise does produce muscle damage, but this damage is a normal event and it is completely reparable. In addition, it leads to an adaptation response. CNS control over muscle may exist to prevent serious injury. Individuals who already have a muscle or joint injury could be at risk in performing maximal high-force eccentric exercise. These individuals, however, may also be at a risk in performing high-force concentric or isometric exercise. It should also be noted that the exercise regimens used in the studies cited above are very strenuous. In many of the studies, 70-consecutive maximal eccentric actions were performed with one muscle group. From these investigations, however, there is no scientific evidence that performance of numerous, repetitive maximal eccentric actions are dangerous to healthy individuals. Moreover, there is certainly no evidence to suggest that testing of eccentric actions where only a few trials of maximal intensity are used should be contraindicated.

Stimulus for Muscle Strength Increase

Moritani and deVries [22] have shown that during the early stages of a strength training program, the increase in strength is due to neural factors. During the later stages, after about 3 to 5 weeks of training, muscle hypertrophy is responsible for strength gains. A review of neural mechanisms in strength development can be found in a recent paper by Jones, Rutherford, and Parker [18].

The exact stimulus for muscle hypertrophy is not known. Jones, Rutherford, and Parker [18] have suggested that hormonal factors may play a role. Release of hormones such as insulin, growth hormone, and testosterone could regulate protein synthesis and degradation to promote muscle growth. Hormones may not be the primary stimulus for hypertrophy but might act in conjunction with local changes in the exercised muscles.

If factors associated with metabolic fatigue were the stimulus for hypertrophy, then one would expect that a metabolically more stressful exercise would induce greater hypertrophy and hence greater strength gains (although there is not a 1:1 relationship between strength and muscle size) than a less metabolically stressful exercise. Training programs using concentric exercise, which is metabolically more costly than eccentric exercise, have not been shown to produce greater strength gain or muscle size than training programs using eccentric exercise. Thus, a purely metabolic mechanism cannot explain the hypertrophic response.

It is tempting to suggest that factors associated with muscle damage could be the stimulus for hypertrophy. Moreover, the adaptation effect (rapid training effect) that has been described for muscle damage (see above), would be an attractive correlate to the hypertrophic response. However, no studies have shown that training using eccentric actions is any more effective in inducing strength gain or hypertrophy than concentric exercise. Thus the adaptation effect observed after eccentric-exercise-induced muscle damage seems unrelated to the stimulus for hypertrophy.

High tension levels have been considered as the stimulus for hypertrophy. However, if high tension alone were the stimulus, eccentric exercise would likely cause more hypertrophy than concentric. There is no evidence for this and, as Stauber [30] has noted, body-builders who use eccentric actions in their training have no larger muscles than weight lifters who avoid eccentric actions. Moreover, increases in cross sectional area of muscle after training with eccentric actions are not greater than increases after concentric actions that produce less tension [16].

The exact stimulus for muscle hypertrophy is not known. It is possible that several factors are involved in a complex interplay of events. For example, there may be a threshold force or tension level that must be achieved which would serve as the primary stimulus for hypertrophy. Then, other factors would come into play and modulate the response.

Strength Requirements for Extended Duration Space Activities, Reentry, and EVA

Exposure to microgravity environments for an extended duration results in muscle atrophy and a decline in muscle function [12]. However, little is known about how various expressions of strength are affected. Because of the lack of gravity, muscle usage will be considerably different, particularly with regard to a lack of eccentric actions. For example, in a one-g environment a person would lift up a weight by contracting the forearm flexor muscles in a concentric action and would lower the weight by having the forearm flexors perform an eccentric action. However, in microgravity, a weight would be lifted with the forearm flexors but to move the weight to the starting position the forearm extensors would act in a concentric manner. Situations in microgravity where eccentric actions may be used, for example, would be to stop the body when it is propelled towards an immovable object.

If there is a preferential lack of eccentric actions performed in microgravity conditions, how does this impact on strength loss, atrophy, and performance—either for EVA or for reentry? It has been shown that exercise programs involving combinations of muscle action modalities are most effective in 19 producing strength gains. Conversely then, will exercises during extended periods of microgravity that do not incorporate eccentric actions be less effective in retarding atrophy and strength loss?

At present, it is difficult to recommend specific training regimens either for performance during space flight or for conditioning prior to space flight. Before such recommendations can be made, knowledge of the effects of prolonged exposure to microgravity on various modalities of strength (isometric, concentric and eccentric) are needed. Also specific performance requirements (i.e., modalities of strength, endurance) needed for EVA and reentry must be identified.

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