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Exercise Science

MUSCLE PHYSIOLOGY AND NEUROMUSCULAR ADAPTATIONS TO EXERCISE

SKELETAL MUSCLE MACROSTRUCTURE

The body's musculoskeletal system is comprised of muscle tissue, connective tissue, nerves, blood vessels, cartilage, and bone. These components function together to support the body, produce motion, and protect vital organs. Skeletal muscles throughout the body, such as the biceps and triceps, consist of many individual skeletal muscle cells, known as muscle fibers. In some muscles, individual muscle fibers extend the entire length of the muscle. The fibers are cylindrical shaped and are approximately the diameter of a human hair. They have many nuclei on their periphery and, thus, demonstrate a striated appearance under low magnification.

Each individual muscle fiber is surrounded by a connective tissue layer called the endomysium. Groups of these muscle fibers are bundled together and are called fasiculi. Each fasiculi can include up to 150 fibers and is covered by a layer of connective tissue called the perimysium. The entire muscle belly is surrounded by a tough tissue structure called the epimysium. This layer of connective tissue gives shape to the muscle. Although these three layers of connective tissue are described separately, they are interwoven as a continuous sheet of tissue.

The endomysium, perimysium, and endomysium layers are all continuous with the tendons at the end of each muscle. Tendons act as a bridge between muscles and bone periosteum. This attachment allows for smooth contraction of the muscle. The transmission of force from the muscle to the bone occurs when the muscle pulls on the tendon, which in turn pulls on the bone periosteum. Therefore, tension developed in one muscle cell is transmitted to the tendon and then to the body's skeletal system to initiate motion.

In order for a muscle contraction to occur, a signal must be sent from the brain to the individual muscle fibers. The transmission of this signal occurs when the brain sends specific information through corticospinal tracts to different regions of the body for skeletal muscle integration. The junction between a motor neuron and the muscle fibers that it innervates is called the neuromuscular junction or motor end plate. Each muscle fiber has only one neuromuscular junction. However, a single motor neuron can innervate many muscle fibers. The motor neuron and the muscle fibers it innervates is called the motor unit. Therefore, all of the muscle fibers of a motor unit contract together when they are stimulated by the motor neuron.

SKELETAL MUSCLE MICROSTRUCTURE

The striated pattern of skeletal muscles results from the interior structure of the muscle fiber. Each muscle fiber consists of cytoplasmic structure called the sacroplasm. This gel-like substance contains contractile components of protein filaments, stored glycogen, fat particles, enzymes, and specialized organelles such as the mitochondria and sarcoplasmic reticulum.

The sacroplasm is also filled with hundreds to thousands of myofibrils, each 1/100th the diameter of a human hair. Each myofibril contains the apparatus that contracts the muscle cell. The two primary components of each myofibril are myofilaments actin and myosin. Myosin filaments are thicker; approximately 1/10,000 the diameter of a human hair. These filaments contain globular heads called cross-bridges. The thinner actin filaments consist of two strands arranged in a double helix. Actin and myosin are organized longitudinally in the smallest contractile unit of the skeletal muscle called the sacromere. Sarcomeres are repeated the entire length of the muscle fiber.

Adjacent myosin filaments anchor to each other at the M-line in the center of the sacromere. Actin filaments are aligned at both ends of the sarcomere and are anchored at an area called the Z-line. This arrangement of actin and myosin gives skeletal muscle its alternating dark and light pattern or striated appearance.

SLIDING-FILAMENT THEORY OF MUSCULAR CONTRACTION

Muscle contraction refers to the activation of the force generation sites within muscle fibers – the cross-bridges. In order for this contraction to occur, actin filaments at the end of each sacromere slide inward on the myosin filament. Each myosin cross-bridge attaches to an actin filament, pulling the fibers even closer together, much like the oar propels a boat through the water. A very small displacement of the actin filament occurs with each flexion of the myosin cross-bridge. Thus, rapid and repeated flexion of numerous cross-bridges must occur along the entire muscle in order for movement to arise.

MUSCLE FIBER TYPES

Not all skeletal muscle fibers have the same physiological and morphological characteristics. Different types of muscles can be identified on the basis of their twitch time, or the maximum velocity at which they shorten. Muscle fibers are defined as being fast-twitch or slow-twitch fibers.

Fast-twitch fibers both develop force and relax rapidly. They have a relatively short twitch time, and are also referred to as type-II fibers. Slow-twitch motor units develop force and relax slowly, therefore having a longer twitch time. These motor units are called type-I fibers.

In addition to their difference in mechanical characteristics, these fibers have a distinct difference in their ability to demand and supply energy for contraction and to resist fatigue. Type I fibers are fatigue resistant and have a high capacity for aerobic energy supply. Type-I muscle fibers also have limited potential for rapid force development and are characterized by low actomyosin myofibrillar ATPase activity and low anaerobic power. In contrast, Type-II motor units have the opposite characteristics. This fiber type fatigues quickly, has low aerobic power, rapid force development, high actomyosin myofibrillar ATPase activity, and high anaerobic power.

The Type II muscle can be further classified into subdivisions. The Type IIa and Type IIb fibers are different mainly in their capacity for aerobic-oxidative energy supply. For example, the Type IIa muscle fibers have a greater capacity for aerobic metabolism and more capillaries surrounding them than a Type IIb fiber. The Type IIa fiber will have a greater resistance to fatigue. For this reason, the postural muscles will have a high composition of Type I fibers, whereas a large muscles like the quadriceps has a mix of both Type I and Type II fibers to allow for both low and high power output activities such as walking and sprinting.

MOTOR UNIT RECRUITMENT DURING EXERCISE

The output of force from a muscle can vary over a wide range. This production of force is essential to the creation of smooth, coordinated patterns of movement. In general, muscular force can be classified in two different ways.

One way to grade force is by varying the frequency of muscle fiber activation. When a motor unit is activated once, the twitch response that occurs does not produce a great deal of force. By increasing the frequency of activation so that the twitch forces are allowed to summate, the end result is greater force developed by the motor unit. This particular method of varying force output is often used in small muscles. At low forces, most of the motor units are activated at a low frequency. The force output of the whole muscle will be intensified by increasing the frequency of firing of the individual motor units. A second way of increasing force occurs through the variation of the number of active motor units. This process is known as recruitment. In larger muscle groups, motor units are activated at near-tetanic frequency when required. Increasing force output is achieved by recruiting additional motor units.

The type of motor unit that is recruited for a specific activity will be determined by its physiological characteristics. For example, a distance runner will recruit slow-twitch motor units to take advantage of their endurance capacity and resistance to fatigue. However, if a runner is a sprinter, the fast-twitch motor units are recruited instead.

PROPRIOCEPTION

Proprioceptors are specialized sensory receptors located within a muscle, tendon, or joint. These receptors are sensitive to pressure and tension in a muscle. They relay information regarding muscle dynamics to the central nervous system. Therefore, the brain is provided with information concerning kinesthetic sense or appreciation of the body in space. Most proprioceptive information is processed at subconscious levels. Therefore, individuals do not have to apply conscious effort to maintain posture or body part positioning.

MUSCLE SPINDLES

A muscle spindle is a type of proprioceptor that consists of several modified muscle fibers that are enclosed in a sheath of connective tissue. The modified fibers are called intrafusal fibers and run parallel to the normal extrafusal fibers. The spindle provides information concerning the muscle's length and its rate of change in length. When a muscle lengthens, the spindles are stretched. This stretching results in the activation of a sensory neuron within the spindle which sends an impulse to the spinal cord to activate a motor neuron response that innervates the same muscle.

Spindles thus indicate the degree to which the muscle must be activated in order to overcome a given resistance. For example, as a given load increases, a muscle is stretched to a greater degree and the engagement of muscle spindles results in greater activation of contraction of the muscle. Muscles that perform a very precise movement have many spindles to help ensure exact control of their contractile activity. One example of muscle spindle activity is the knee-jerk reflex. By tapping the tendon of the knee extensor muscle group below the patella, the muscle spindle fibers are stretched. This causes the activation of the extrafusal muscle fibers in the quadriceps. There is a knee jerk reflex response, as these fibers actively shorten.

GOLGI TENDON ORGANS

A golgi tendon organ is a proprioceptor that is located in a tendon near the myotendinous junction. The golgi tendon organs are in arranged in a series with extrafusal muscle fibers. Golgi tendon organ activation occurs when the tendon attached to an active muscle is stretched. As tension increases in the muscle, activation of the GTO also increases. This causes the sensory neuron of the golgi tendon organ to synapse with an inhibitory interneuron at the spinal cord level. The end result is a reduction in tension within the muscle and tendon.

The muscle spindle facilitates activation of the muscle while the golgi tendon organ inhibits muscle activation. The golgi tendon organ inhibitory process acts as a protective mechanism from the development of excessive tension. When forces are low, the effect of the golgi tendon organ is minimal. However, with a heavy load applied to a muscle, a reflexive inhibition mediated by the GTO's will cause the muscle to relax. The ability of the motor cortex to override the inhibition may be one of the fundamental adaptations to heavy resistance training.

NEUROMUSCULAR ADAPTATIONS TO EXERCISE

Skeletal muscle adaptations to physical conditioning have generally been divided into two categories. Adaptations occur as a result of the performance of either resistance or aerobic endurance exercise.

ADAPTATIONS TO RESISTANCE TRAINING

One of the most well recognized results of resistance training is an increase in muscle mass. This occurs through the enlargement of muscle fibers, not by an increase in fiber number. The increase in cross-sectional area of the muscle fibers allows for an increase in the muscle's ability to develop force. However, muscle fiber hypertrophy does not occur uniformly between the two major fiber types. Studies have shown that with resistance training, the fast-twitch fibers show a greater increase in size than slow-twitch fibers. Therefore, the potential for muscle enlargement may reside in the relative proportion of fast-twitch fibers within an individual's muscles. The differences in muscle fiber composition and number may partially explain the marked variability among athletes in their muscular hypertrophy when conditioning.

Even though the majority of studies of hypertrophic response to resistance training have been conducted on males, several recent studies of females have also demonstrated significant increases in cross-sectional area of muscle fibers as a result of heavy resistance training. The relative increase in muscle fiber size in response to short-term training has been found to be comparable between males and females. This comparison may not be obvious visually because of the greater proportion of body fat in females.

It has also been found that the extent of the hypertrophic response to resistance training is influenced by the time course of training. An increase in strength during the first one to two months of conditioning performed by a previously sedentary individual is not usually accompanied by muscle fiber hypertrophy. It appears that neural factors must adapt in some manner to allow for a change in strength. This adaptation actually will result in less muscle being used to lift a given sub-maximal load during the early phases of strength training. As a result, greater loading is imposed per unit of muscle. This will slowly promote hypertrophy. After approximately six to eight weeks of training, muscle fiber hypertrophy occurs and contributes to an increase in strength.

Conversely, it is more difficult to demonstrate significant increases in muscle size and strength in weight-trained athletes. One study showed that after a two year period of heavy resistance training in a group of athletes, an increase in strength was achieved. However, muscle fiber hypertrophy contributed little to increased lifting performance. Again the neural factors accounted for the improvement in performance. Here, the contribution of conditioning to optimal performance can be achieved only if intensity is maximal.

An athlete's maximal aerobic power does not change with resistance training. And it does not appear to impair the muscle's ability to develop maximal aerobic power either. In fact, athlete's that combine aerobic and resistance training actually enhance the positive adaptations to aerobic endurance training. One study has demonstrated that when competitive distance runners added lower-body resistance training to their conditioning program, several aspects of short-term aerobic endurance improved. The resistance training may simply increase a distance runner's ability to sprint at the end of a race.

ADAPTATIONS TO AEROBIC ENDURANCE TRAINING

One of the basic adaptive responses to aerobic endurance training seen in individuals is the increase in aerobic capacity of the trained muscles. After training, this adaptation will allow the athlete to perform at a maximum level of exercise intensity with greater ease. More importantly, after training, it may be easier for an athlete to exercise at a greater intensity of a now higher maximal aerobic power.

When an athlete's maximal oxygen uptake is measured before and after aerobic endurance training, it may not accurately demonstrate their ability to perform during any competition. In a marathon runner that has trained at 75% of their maximal oxygen uptake, they may be able to perform at 80% of their maximal aerobic power. This adaptation occurs as a result of glycogen sparing within the muscle. Less glycogen is used during exercise which prolongs the performance and reduces buildup of lactic acid. Also, the increase in fat utilization contributes to glycogen sparing as well.

The increase in the aerobic capacity of muscles that occurs after aerobic endurance training occurs in both fast-twitch and slow-twitch muscle fibers. Since slow-twitch fibers have an inherently higher aerobic capacity, they are preferentially recruited during aerobic activity. However, if the intensity of the exercise is significant, fast-twitch fibers, especially type-IIb, will be recruited. Their aerobic capacity also increases with training.

When an exercise program includes intense aerobic exercise and resistance training, the change in strength will be less than would occur if only resistance training had been performed. It is not suggested that strength and power athletes condition with intense aerobic endurance programs. Studies have also shown that when elite endurance athletes discontinue aerobic training, an increase in their muscular strength and power is achieved.

CLINICAL CONNECTION

When evaluating and treating an injured athlete, the physical therapist has a clear understanding of both muscle physiology and adaptations that occur in muscle with exercise programs.

During the final stages of recovery from an injury, the therapist will design an exercise program that is sport specific when combining appropriate resistance and aerobic endurance exercise.

ORTHOPEDIC & SPORTS PHYSICAL THERAPY ASSOCIATES, INC.

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News briefs

OSPTA thanks Mr. Mark Aaron, PT for his contribution for the newsletter.

On November 7, 2011, OSPTA moved its Jefferson office to the K Mart Plaza in Pleasant Hills, Pa. The office will be located adjacent to the Jefferson Wellness Center. The new office will be offering physical therapy, certified hand therapy, vestibular rehabilitation, lymphedema treatment and a Women's Health Program.

At select offices, OSPTA offers specialty programs in Pilates, Vestibular Rehabilitation, Pediatrics, Lymphedema, Women's Health, Certified Hand Therapy and a Sportsmetrics program to prevent ACL injuries.

To find an office close to you, check our website: www.osptainc.com or call 1-800-337-6452.

In addition, OSPTA Home Healthcare offers homecare services. The toll free number 1-866-483-4859.

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