A Primer on Muscles

by Jason R. Karp, PhD

Why do some people run faster and jump higher?

When I was a kid, I used to show girls my biceps. Boys do silly things to impress girls. As adults, both men and women search for countless ways to make their biceps, and the rest of their muscles, look appealing to themselves and each other. To most people, muscles are external structures, admired from the outside. But what lies *within* a shapely biceps is a wonderfully complex structure responsible for everything from metabolism to movement.

While the biceps may be the poster child for strong, attractive muscles, there are more than 600 muscles in your body, from the large vastus lateralis on the anterior lateral portion of your thigh to the small orbicularis oculi that closes your eyelids and wrinkles the skin on your forehead. Ever wonder how all of these muscles work?

Muscle Physiology

Humans have three different kinds of muscles—**skeletal** muscles, which connect to bones; **cardiac** (heart) muscle; and **smooth** muscles, which line blood vessels and the gastrointestinal and urinary tracts. Skeletal muscles, which comprise about 40% of your body weight, are very organized. Microscopic proteins are bundled together to form a myofibril, many myofibrils are bundled together to form a fiber, many fibers are bundled together to form a fascicle, and many fascicles are bundled together to form the whole muscle. This organization permits an enormous diversity of movements, from threading a needle to running a marathon. Of all the muscle’s compartments, the fibers are the ones that distinguish between people, since there are different fiber types, with the exact mix being genetically determined.

Apart from thinking, every human activity requires a muscle action, called a **contraction.** The contraction is initiated by impulses, called action potentials, which are conveyed by a neural cell called a motor neuron. Women who have given birth know all too well what a contraction is. Labor pains are the contractions of the smooth muscles of the uterus.

In 1957, Nobel Prize–winner Andrew Huxley discovered that muscles contract and produce force through the interaction of two microscopic proteins—actin and myosin. **Myosin,** which looks like an oar with its paddle at an angle, attaches to **actin,** which looks like two strings of pearls twisted together. The paddle portion of myosin binds to actin and pulls it so that actin slides past myosin. The mechanism is much like the movement of a rowboat’s oars in water, except that the water (actin) moves past the stationary boat (myosin). This movement happens among millions of actin and myosin proteins within each fiber, with all the actin proteins from opposing sides moving closer together, causing the entire muscle to shorten in a concentric contraction. The more actin and myosin proteins you have in your muscles, the more force they can produce. A boat with eight oars stroking the water is stronger and more powerful than a boat with two.

Skeletal muscle fibers either contract or they don’t. There is no such thing as a partial contraction. Like a light, fibers are either on or off. You vary the amount of muscle force by varying the number of motor units you contract and the frequency with which those motor units are recruited by the central nervous system, not by varying their degree of contraction. Smooth muscles, on the other hand, can contract partially. They have a dimmer on their light switch, called tone. This characteristic comes in handy when trying to do such things as regulate blood pressure, which is elegantly accomplished by subtle alterations in the dilation and constriction of blood vessels. While “toning your muscles” at the gym has become a common expression, it is a physiological impossibility, since skeletal muscles cannot exhibit tone.

These muscles contract and produce force in three ways. When you are lifting a weight or working against a resistance, the muscles shorten in a **concentric contraction.** When you are lowering a weight or yielding to gravity, they lengthen in an **eccentric contraction.** When you unsuccessfully try to lift a weight or push against something immovable, your muscles remain the same length in an **isometric contraction.** Of the three, eccentric contractions are the strongest and cause the most muscle damage and soreness, as the myosin is pulled apart from its binding site on actin. That’s why running downhill makes your muscles sorer than running uphill.

Muscle Fiber Type

Ever notice that some of your clients can do cardiovascular exercise for long periods of time but get tired quickly when lifting heavy weights? Or that others can lift heavy weights but run only 5 minutes on the treadmill? The reason why some clients can run faster or longer or get bigger muscles more easily than others lies in their muscles. The specific types of fibers that make up individual muscles greatly influence the way your clients adapt to their training programs. To design the optimal program for each of your clients, it is important to understand some of the complexity of skeletal muscles.

Humans have three different types of muscle fibers (as well as gradations between them), the proportions of which are genetically determined. **Slow-twitch (type I)** fibers are recruited for aerobic activities and therefore have many characteristics needed for endurance, such as perfusion with a large network of capillaries to supply oxygen, lots of myoglobin to transport oxygen, and lots of mitochondria—the aerobic factories that contain enzymes responsible for aerobic metabolism. True to their name, slow-twitch fibers contract slowly but are very resistant to fatigue.

Fast-twitch (type II) fibers are recruited for anaerobic activities and therefore have many characteristics needed for strength, speed and power, such as large stores of creatine phosphate and glycogen and an abundance of enzymes involved in the anaerobic metabolic pathway of glycolysis. They contract quickly but fatigue easily. Fast-twitch fibers come in two forms: **fast-twitch A (type IIa)** and **fast-twitch B (type IIb).** Fast-twitch A fibers, which represent a transition between the two extremes of slow-twitch and fast-twitch B fibers, have both endurance and power characteristics. They are recruited for prolonged anaerobic activities that require relatively high forces, such as running a long, controlled sprint and carrying heavy objects, and are more fatigue-resistant than the fast-twitch B fibers, which are recruited only for short, intense activities, such as jumping, sprinting at full speed and lifting very heavy weights.

The differences in the contraction speeds that give the fibers their names are partly explained by the rate of release of calcium by the sarcoplasmic reticulum (the muscle's storage site for calcium) and the activity of the enzyme that breaks down ATP (adenosine triphosphate) inside the myosin head (myosin ATPase). Both calcium release and myosin ATPase activity are faster and greater in the fast-twitch fibers (Fitts & Widrick 1996), enabling them to contract faster than their slow-twitch counterparts. In addition to the three major divisions of muscle fibers, there are also hybrid forms of these fiber types (Fry 2004).

You can see the difference between the fiber types during Thanksgiving—the dark meat of your turkey dinner, so colored because of its myoglobin content, is composed of slow-twitch fibers, and the white meat is composed of fast-twitch fibers. But if your clients want to run a great marathon, they shouldn't reach for the dark meat too quickly. Unfortunately, the type of meat they eat has no impact on their endurance or sprinting ability.

Muscle fiber composition has a large genetic component (Simoneau & Bouchard 1995). People are born with specific proportions of slow-twitch, fast-twitch A and fast-twitch B fibers, and these proportions vary from person to person. However, the exact ratios may be amenable to change with specific training. Fiber type also varies from muscle to muscle, based on the intended function. For example, muscles involved in maintaining posture, like those of the abdominal and lumbar-back regions, are composed mainly of fatigue-resistant slow-twitch fibers and are therefore best suited for endurance training.

It is well known that aerobic athletes have a greater proportion of slow-twitch fibers, while anaerobic athletes have more fast-twitch fibers (Ricoy et al. 1998). The greater proportion of fast-twitch fibers in the anaerobic athletes enables them to produce greater muscle force and power than their slow-twitch-fibered counterparts (Fitts & Widrick 1996). Fast-twitch fibers are the main contributors to force production during maximal ballistic movements, such as sprinting and jumping.

Muscle fiber type influences the amount of force produced at any given velocity of movement. During a dynamic contraction, when the fiber is either shortening or lengthening, a fast-twitch fiber produces more force than a slow-twitch fiber (Fitts & Widrick 1996). Under isometric conditions, during which the length of the muscle does not change while it is contracting, slow-twitch fibers produce exactly the same amount of force as fast-twitch fibers. Furthermore, at any given velocity of movement, the force produced by the muscle increases with the percentage of fast-twitch fibers and, conversely, at any given force output, the velocity increases with the percentage of fast-twitch fibers.

However, regardless of fiber-type distribution, as the velocity of movement increases, the force produced by the whole muscle decreases (Cress, Peters & Chandler 1992). In other words, as we move faster, muscle force production decreases. That's why we must move slowly to lift a heavy weight. However, at any given speed of movement, the more fast-twitch fibers there are inside the muscle, the greater the force production will be. So, someone with 90% fast-twitch fibers in a muscle can produce more force at a specific speed of movement than someone with 60% fast-twitch fibers.

Muscle Fiber Recruitment

Instead of recruiting individual muscle fibers to perform a specific task, we recruit motor units—groups of muscle fibers innervated by a single motor neuron. All muscle fibers of a motor unit are of the same type (slow-twitch, fast-twitch A or fast-twitch B). This recruitment of motor units is controlled by neuromuscular processes, ultimately leading to the production of muscular forces.

Motor neurons originate in the central nervous system and terminate in skeletal muscles. The space where the motor neuron and the muscle meet is aptly named the **neuromuscular junction.** At rest, sodium ions (Na^+) are most heavily concentrated on the outside of the nerve membrane, causing it to be electrically positive, while the inside of the nerve, which contains potassium ions (K^+), is electrically less positive, or negative with respect to the outside. Under the influence of the neurotransmitter acetylcholine, which is released at the neuromuscular junction, the muscle membrane becomes highly permeable to Na^+, causing Na^+ to rush inside the membrane.

As a result, the outside of the membrane becomes negative and the inside positive, reversing its polarity. This reversal of polarity is called **depolarization** and results in the formation of an **action potential.** The action potential propagates deep inside the muscle fiber, ultimately leading to muscle contraction as calcium is released from the sarcoplasmic reticulum.

Motor units are recruited along a gradient. During voluntary isometric and concentric contractions, the pattern of recruitment is controlled by the size of the motor unit (specifically, the size of the motor axon supplying the motor unit), a condition known as the **size principle** (Nardone, Romano & Shieppati 1989).

Small motor units (those with a small motor axon diameter), which contain slow-twitch muscle fibers, have the lowest firing threshold and are recruited first. Demands for larger forces or faster speeds are met by the recruitment of increasingly larger motor units. The largest motor units (those with the largest axon diameter), which contain fast-twitch B fibers, have the highest firing threshold and are recruited last. Thus, regardless of the exercise intensity or movement speed, slow-twitch motor units are always recruited first.

When the exercise intensity or speed is low—during treadmill jogging, for example—slow-twitch motor units may be the only ones that are recruited. When the exercise intensity or speed is high—during sprinting or heavy weightlifting, for instance—slow-twitch motor units are recruited first, followed by fast-twitch A and, if needed, fast-twitch B units. Fast-twitch fibers are also recruited to pick up the slack of fatiguing slow-twitch fibers, even when the intensity and speed are low.

For example, during long-distance running, or even when you are holding a 1-pound dumbbell in your hand, slow-twitch fibers are initially the only fibers recruited. But run down the street or hold that 1-pound dumbbell long enough and the slow-twitch fibers will eventually fatigue, forcing recruitment of fast-twitch fibers to continue the task. Thus, the size principle gives us some insight into how to train fast-twitch fibers—go intense, go fast or go long.

There is some evidence to suggest that the size principle may be altered or even reversed during eccentric contractions or ballistic movements, such that fast-twitch motor units are recruited before slow-twitch motor units (Grimby & Hannerz, 1977; Nardone, Romano & Shieppati 1989; Smith et al. 1980). It seems that a preferential recruitment of fast-twitch motor units, if it exists, is influenced by the speed of the eccentric contraction and occurs only with fast speeds (Nardone, Romano & Shieppati 1989).

Determining Fiber Type

The only way to determine fiber types directly is with a muscle biopsy, during which a needle is stuck into the muscle and a few fibers are plucked out to be examined under a microscope. However, since research using isokinetic dynamometers or electrical stimulation has repeatedly shown that there is a significant, positive relationship between the proportion of fast-twitch fibers and muscular strength and power (Coyle, Costill & Lesmes 1979; Gerdle, Wretling & Henriksson-Larsen 1988; Gregor et al. 1979; Suter et al. 1993), it is possible to estimate your clients' fiber types without a biopsy by measuring their performance on muscular strength tests (see the sidebar "Determining Muscle Fiber Type").

Training Muscles

Fiber type proportions will play a major role in the amount of weight your clients can lift, the number of repetitions they can complete per set, and the desired outcome (e.g., increased muscular strength or endurance). For example, a client with a greater proportion of fast-twitch fibers won't be able to complete as many repetitions at a given percentage of his or her one-repetition maximum (1 RM) as will a client with a greater proportion of slow-twitch fibers—and therefore will not attain as high a level of muscular endurance as will the slow-twitch-fibered client.

Similarly, a client with a greater proportion of slow-twitch fibers won't be able to lift as heavy a weight or run as fast as will a client with a greater proportion of fast-twitch fibers—and therefore won't be as strong or powerful as will the fast-twitch-fibered client.

To focus on a specific goal, your clients' training should reflect their physiology. For example, if a client has more slow-twitch fibers, that person is best suited for endurance activities, and his or her training should focus on aerobic exercise or training for muscular endurance, using more reps of a lighter weight. If a client has more fast-twitch fibers, that person is best suited for anaerobic exercise and weight training for muscular strength, using fewer repetitions of a heavier weight. However, if a client has more slow-twitch fibers but wants to get stronger and faster, you should try to increase the intensity of the weight training workouts and the speed of his or her cardio workouts as training progresses. Conversely, if a client has more fast-twitch fibers but wants to increase endurance, you should try to increase the duration of the cardio workouts and the number of repetitions in the strength training program as training progresses.

That said, there is evidence that both the structure and metabolic capacity of individual muscle fibers can adapt specifically to different types of training. For example, aerobic training increases the Krebs cycle enzyme activity of slow-twitch fibers, while sprint training increases the glycolytic enzyme activity of fast-twitch fibers (Holloszy & Coyle 1984; MacDougall et al. 1998). While it does not seem possible to convert a slow-twitch fiber into a fast-twitch fiber, or vice versa—making it impossible for an elite marathon runner to become an elite sprinter or vice versa—there does seem to be some plasticity between the fast-twitch fiber subtypes.

For example, maximal or near-maximal strength training has been shown to convert fast-twitch B fibers to fast-twitch A fibers (Adams et al. 1993; Fry 2004; Grimby & Hannerz 1977; Staron et al. 1990) owing to changes in the myosin heavy-chain isoform (Adams et al. 1993; Andersen & Aagaard 2000), suggesting that training can cause a genetic transformation among the fast-twitch fiber subtypes.

There is some interesting evidence from research performed on rabbits that a slow-twitch fiber can be made to *behave* like a fast-twitch fiber if the nerve that supplies the slow-twitch fiber is surgically interchanged (cross-reinnervated) with one that supplies a fast-twitch fiber (Bacou et al. 1996), suggesting that the behavior of muscles is greatly influenced by the activity of their nerves. However, no similar studies have been performed on humans, and there is no evidence that training has a similar effect on muscle fibers.

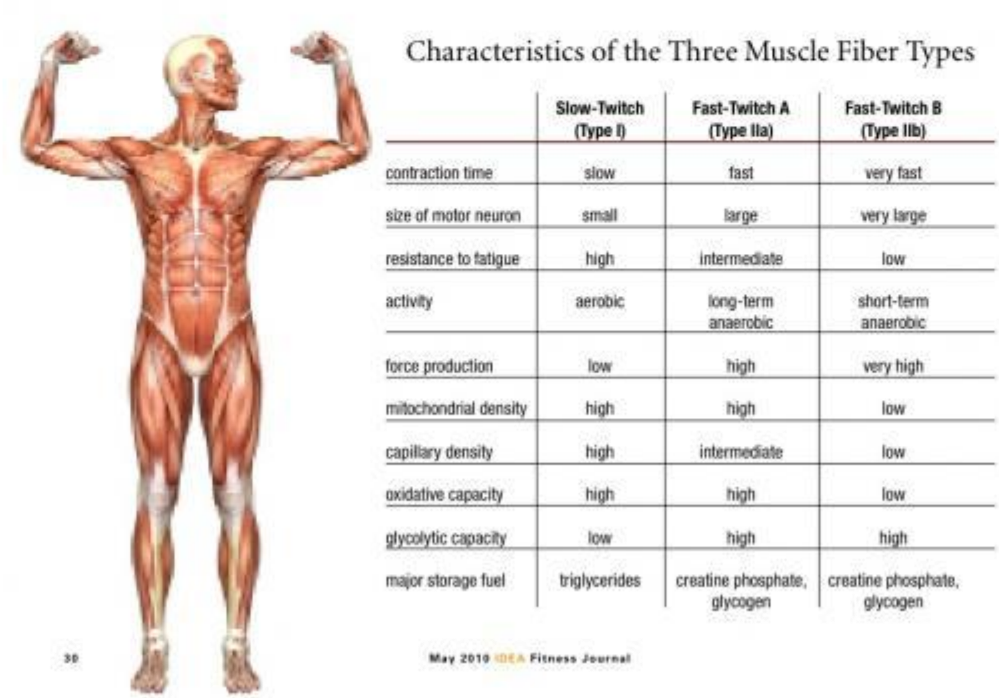
Although slow-twitch and fast-twitch fibers cannot be changed from one to another, training can change the amount of area taken up by each fiber type in the muscle. In other words, there can be *selective hypertrophy* of fibers based on the type of training. For example, your client may initially have a 50-50 mix of fast-twitch and slow-twitch fibers in a muscle. Since fast-twitch fibers have a larger cross-sectional area than slow-twitch fibers, more than 50% of that muscle’s area may be fast-twitch and less than 50% may be slow-twitch (Pipes 1994).

However, following an intense strength training program, the *number* of fast-twitch and slow-twitch fibers will remain the same (still 50-50), but the *cross-sectional area* will change (Pipes 1994). This happens because fast-twitch fibers increase their cross-sectional area much more than do slow-twitch fibers (McComas 1996). Depending on the specific training stimulus, the cross-sectional area of the muscle may now be 75% fast-twitch and only 25% slow-twitch. This change will lead to greater strength but decreased endurance.

In addition, since the *mass* of fast-twitch fibers is greater than that of slow-twitch fibers, your client will gain muscle mass. Hypertrophy occurs only in those muscle fibers that are overloaded, so the fast-twitch B motor units must be recruited during training in order to be hypertrophied. Training with a low or moderate intensity will not necessitate the recruitment of fast-twitch B motor units. Therefore, the training intensity must be high (fewer than 10–12 RM).

If an untrained client trains for muscular endurance (and therefore has minimal recruitment of fast-twitch fibers), the slow-twitch fibers will hypertrophy, resulting in a greater relative cross-sectional area of slow-twitch fibers and a smaller relative area of fast-twitch fibers. The area of the muscle, which may have been 65% fast-twitch and 35% slow-twitch before training, may change to 50% fast-twitch and 50% slow-twitch following training. The endurance capability of the muscle will increase, while its strength will decrease. However, your client will lose some muscle mass because slow-twitch fibers are smaller than fast-twitch fibers (McComas 1996).

To maximize your clients' training, tailor it to match their muscle fiber compositions. If they train smart enough, not only will they have the best-looking biceps of all their friends; they'll also have something interesting to talk about over the next holiday dinner.



Characteristics of the Three Muscle Fiber Types

	Slow-Twitch (Type I)	Fast-Twitch A (Type IIa)	Fast-Twitch B (Type IIb)
contraction time	slow	fast	very fast
size of motor neuron	small	large	very large
resistance to fatigue	high	intermediate	low
activity	aerobic	long-term anaerobic	short-term anaerobic
force production	low	high	very high
mitochondrial density	high	high	low
capillary density	high	intermediate	low
oxidative capacity	high	high	low
glycolytic capacity	low	high	high
major storage fuel	triglycerides	creatine phosphate, glycogen	creatine phosphate, glycogen

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SIDEBAR: Determining Muscle Fiber Type

Establish your client's one-repetition maximum (1 RM, the heaviest weight he or she can lift just once) for each muscle group. Have that client do as many repetitions at 80% of 1 RM as possible.

- < 7 reps: muscle group = > 50% fast-twitch fibers
- > 12 reps: muscle group = > 50% slow-twitch fibers
- 7–12 reps: muscle group = 50-50 fast-twitch and slow-twitch fibers

In addition to the above method, discuss the following with your client:

1. Are you able to do lots of repetitions when lifting weights, or do you fatigue after a few?

If the former, you probably have more slow-twitch fibers. If the latter, you have more fast-twitch fibers.

2. Are you better at sprint and power activities or at endurance activities?

If the former, you have more fast-twitch fibers. If the latter, you have more slow-twitch fibers.

3. Which type of workouts feel easier and more natural: (a) long, aerobic workouts and light weights with lots of reps or (b) sprints and heavy weights with few reps?

If you answered (a), you have more slow-twitch fibers. If you answered (b), you have more fast-twitch fibers.

4. Which workouts do you look forward to more: (a) aerobic/endurance workouts or (b) anaerobic/strength workouts?

If you answered (a), you have more slow-twitch fibers. If you answered (b), you have more fast-twitch fibers. (From observation, people tend to get excited about tasks at which they excel, while they feel more anxious about tasks that are difficult.)

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