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Built to Move

What do myofibrils have to do with push-ups? Dr. Lon Kilgore explains how our bodies are constructed to produce movement.

Dr. Lon Kilgore

One of the reasons I do what I do is simply because I wanted to know how to make myself a better athlete. From the age of 11, I read anatomy and biology books. I read them not for fun but to improve my competition fitness in wrestling and weightlifting. Even in school I took elective classes I thought would help me figure things out. In high school I took advanced biology, and my senior research project was investigating the effect of different salt solutions and concentrations thereof on force production in isolated frog muscle preps.

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From my earliest recollections, I wanted to know how muscle was built and how it worked. I wanted to know how I could make things move.

The Role of the Cell

To understand how things move we first need to take a little look at how muscles are constructed—a little anatomy lesson, if you will.

Muscles are composed of thousands and thousands of individual muscle cells. Small, tiny muscles have a few thousand cells that can be less than a centimeter long. Big, massive muscles such as the latissimus dorsi, which covers a huge portion of the back, will have millions of muscle cells that can be up to 30 centimeters (about a foot) in length. All together, muscle accounts for about 40 percent of total body weight in an average human.

Let's dissect the muscle down to the cellular level, look at how a cell is built, identify its basic components and briefly examine what each part does.

With his 1665 treatise *Micrographia*, Antoni van Leeuwenhoek provided us with the first glimpse at the primary building block of living things: the cell. It took about 150 years of further study and experimentation by many scientists before enough evidence was acquired to allow zoologist Theodor Schwann to postulate in 1839 that "the elementary parts of all tissues are formed of cells." Schwann's works (along with the works of botanist Matthias Jakob Schleiden) led to modern cell theory, where the cell is considered to be the smallest structure having all the properties of living things. Those properties are:

- Homeostatic control, or the ability to regulate the organism's internal environment
- Organismic composition based on one or more cells
- Metabolic activity, or the consumption of energy through conversion of non-living materials into cellular components
- Capacity for growth
- Capacity for adaptation, or the ability to alter form, function or both over time in response to environmental challenges
- Responsiveness to external stimuli
- Capacity for reproduction, or the ability to produce new organisms.

The Anatomy of the Cell

We are interested here in learning how the typical muscle cell is built, so we will consider only the basic parts of the cell. We want to understand the anatomy of the cell, not delve into the intricacies of molecular and cellular biology.

Several early researchers identified common structures of all observed cells: the cell membrane, cytoplasm and deoxyribonucleic acid (DNA), although these terms were not used at the time (Figure 1).

Cell membrane

Mammalian cells have a bordering and constraining two-layer membrane made of phospholipids (phosphate containing fats/oils). The cell membrane contains the components of the cell and is selectively permeable. It allows some materials to pass into or out of the cell while excluding other materials from passage. All components of the cell are contained within the cell membrane. Anything the cell consumes or creates for export must pass through the cell membrane. The cell membrane can also be called the "plasmalemma."

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Cytoplasm

Inside the cell membrane is a complex collection of substances suspended or dissolved in water called cytoplasm. Other sub-cellular structures are suspended in the cytoplasm, which is also where the first steps of cellular respiration (energy metabolism) take place. When discussing the cytoplasm of muscle cells, the term "sarcoplasm" is frequently used.

DNA

All cells contain DNA, or genetic material. In the most simple cells, DNA appears as a single loop floating free in the cytoplasm. In mammalian cells, like those which make up our bodies, numerous strands of DNA are encapsulated

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within a membrane-bound special structure called the nucleus. DNA is essential for life because DNA makes ribonucleic acid (RNA), which makes protein, which in turn makes function. In the most basic sense, DNA controls anatomy (how things are built) and physiology (how things work).

The invention of the oil-immersion microscope lens in 1870 led to a flurry of discovery in the late 19th century, including the elucidation of other structures, or "organelles," that comprise the mammalian cell.

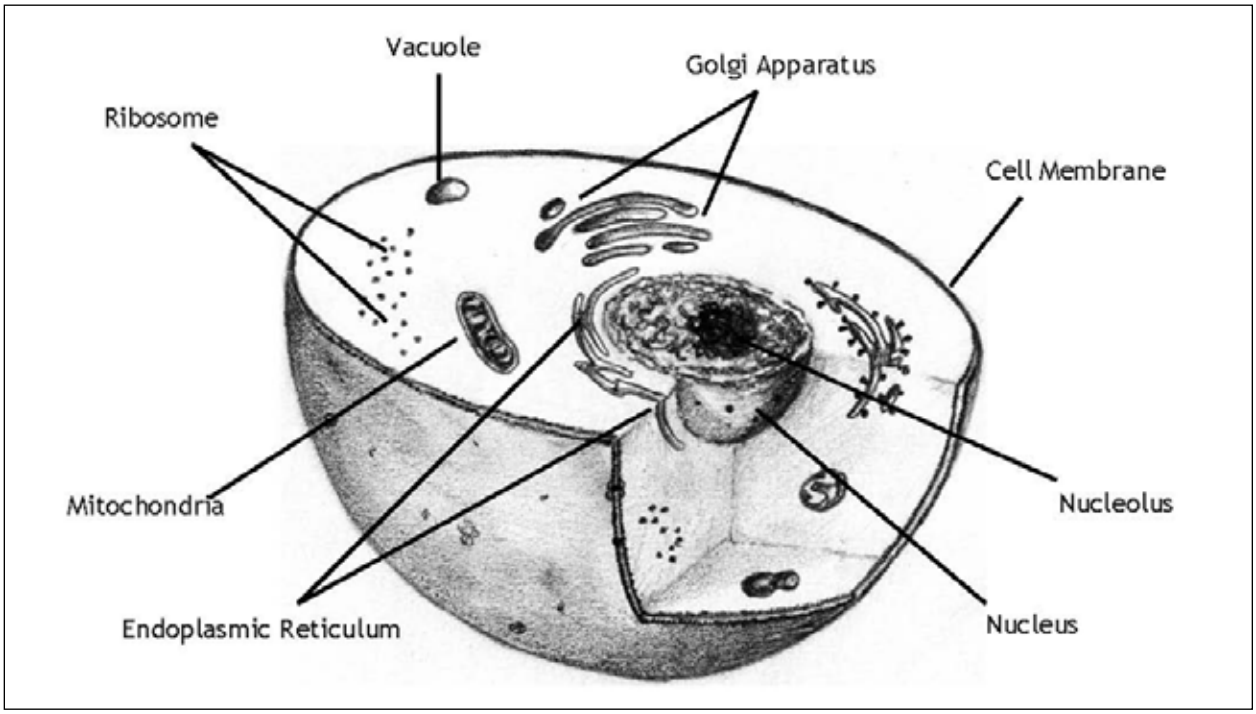
Organelles are well-defined and large-scale structures (relative to the size of an individual cell) that carry out a specific set of functions within the cell. Many organelles are "membrane bound"—completely surrounded by a membrane. Membrane-bound organelles are crucial as they allow different sets of biochemical reactions to be separated from each other so that they do not interfere with each other during simultaneous operation.

A good analogy here would be a factory where different chemicals are kept in separate vats and mixed in separate and sequential mixing containers before a final product is produced. The different compounds and reactions involved in manufacturing the product are kept isolated from each other to keep the factory from producing a random mess of chemical goo.

Compartmentalization of biochemical compounds and processes within membrane-bound organelles prevents interference between different reaction pathways, provides the opportunity for sequential reaction control, and allows the cell to produce compartments with differing internal environments specific to each reaction's efficient completion.

Endoplasmic Reticulum

The basic structure of the endoplasmic reticulum is an extensive membrane network of sac-like structures called cisternae. Like the plasma membrane, the endoplasmic reticulum membrane is composed of phospholipids and



Dr. Lon Kilgore

Figure 1: Schematic of mammalian cell organelles.

The prototypical representation we see in our textbooks and above does not show the true reality of how organelles are distributed in the muscle cell. Nuclei are pressed up against the inside of the cell membrane and the other organelles are crammed between the contractile elements.

creates a bounded space, a networked lumen separate from the surrounding cytosol. There are three types: rough endoplasmic reticulum (having associated ribosomes—see later description), smooth endoplasmic reticulum (having no associate ribosomes), and sarcoplasmic reticulum (found in skeletal muscle).

The rough endoplasmic reticulum plays a major role in producing lysosomal enzymes, secreted cellular proteins and membrane proteins, and it participates in glycosylation (adding carbohydrate to proteins). The smooth endoplasmic reticulum functions in many metabolic processes, most notably the synthesis of lipids and metabolism of carbohydrates. The sarcoplasmic reticulum is a variant found specifically in muscle.

These variants differ in the composition of the proteins bound to their membranes and contained within their lumens. This difference in proteins present alters their respective functions. The smooth endoplasmic reticulum is a synthetic center, and the sarcoplasmic reticulum is a regulatory center for calcium ion storage. The large stores of calcium within the sarcoplasmic reticulum can be rapidly released into the sarcoplasm, which in turn initiates contraction in muscle cells.

Golgi Apparatus

This organelle is composed of membrane-bound vesicles. Normally a few of these flattened sacs (between five and eight) will be in very close proximity, but it has been observed that several dozen can be stacked in some instances in some cells. The Golgi apparatus takes vesicles from the endoplasmic reticulum, fuses with them and modifies the resulting contents before delivering them to their intended destination, which may include dumping the contents outside the cell. They also assist in lipid transport in the cell and in creating lysosomes.

Mitochondria

A mitochondrion has a phospholipid bi-layer membrane (outer and inner). The layers have different compositions (different lipids and embedded proteins present) and therefore differing functions. Five distinct compartments are present within mitochondria: outer mitochondrial membrane, inner mitochondrial membrane, inter-membrane space (between the outer and inner membranes), cristae (the folding of the inner membrane) and the matrix (area within the inner membrane).

Mitochondria numbers vary by location and cell type. A huge number of mitochondria are found in the liver, where they can comprise up to about 20 percent of the total cell volume. They can also be found between the myofibrils (protein filaments) of muscle. They are often depicted as sausage-shaped, but their actual shape varies according to how and where they are associated with cytoskeletal elements. The most prominent function of mitochondria is rooted in energy metabolism. A set of reactions intimately involved in ATP production (known as the citric acid cycle or Kreb's cycle) and the electron transport system occur within the mitochondria.

Vacuoles

These are membrane-bound compartments serving a variety of secretory, excretory and storage functions. They may be called on to remove structural debris or waste from the cell, isolate harmful substances, and store or release ionic molecules to maintain pH balance, along with other housekeeping functions.

Nucleus

The nucleus is the largest cellular organelle in mammalian cells and contains nearly all the cell's genetic material or DNA (the mitochondria contain some DNA). It has an average diameter somewhere between 11 to 22 micrometers and comprises about 10 percent of the typical cell's total volume. The nucleus contains a viscous liquid, similar to cytoplasm, called nucleoplasm. Suspended in the nucleus is a sub-organelle—the nucleolus that is the site of ribonucleic acid synthesis and ribosomal assembly. Some cells, like red blood cells, are anucleate (no nuclei present). Others, like cardiac muscle cells, are mononucleate (one nucleus present). Still others, like skeletal muscle cells, are multi-nucleate (many nuclei present).

Ribosomes

These small, non-membranous organelles were discovered in 1955 after the invention of the electron microscope. Ribosomes, themselves built partially from ribonucleic acid (RNA), build proteins from genetic instructions passed from DNA to RNA. Ribosomes can be found "free" (suspended in the cytosol), or they can also be bound to the endoplasmic reticulum, giving it the appearance of roughness, and thus the name "rough endoplasmic reticulum."

Lysosomes
These membrane-bound organelles contain acid hydrolases (digestive enzymes) and work to digest worn-out organelles, food particles, or viral or bacterial pathogens that have been engulfed by the cell. The membrane of the lysosome allows a separation of the acidic lysosomal lumen and the neutral cytoplasmic environments.

Myofibrils
Muscle fibers diverge from the physical shape of the prototypical mammalian cell. They generally appear as long cylindrical cells with tapered ends. Their scale is fairly large, to the point of visibility with the naked eye (Figure 2).

Each muscle cell, or myofiber, contains long filaments of proteins called myofilaments, which facilitate human movement. Myofibrils are composed of two basic types of myofilaments: thick and thin. Thick myofilaments are made primarily of the protein myosin held in place, relative to other myofilaments, by titin filaments (another specialized protein). Myosin looks much like two sets of golf clubs, each gathered up with the club-heads protruding outwardly at different levels and angles. The sets are connected handle-to-handle.

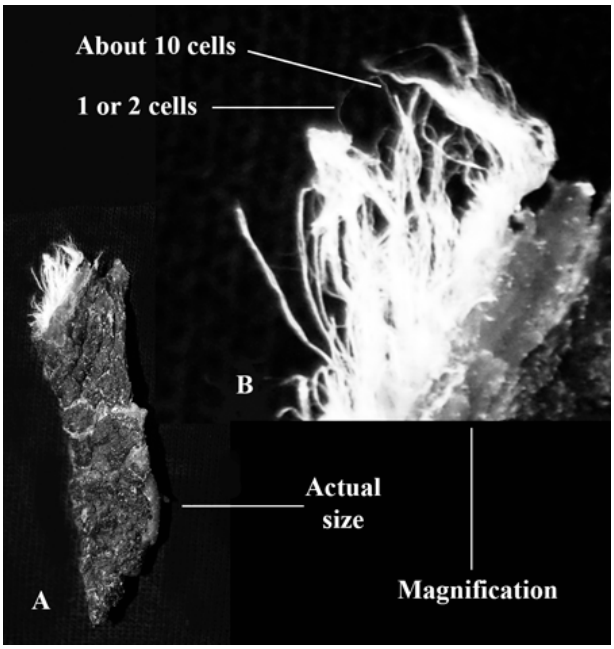


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Figure 2: Tearing a very dry piece of beef jerky reveals small groups of muscle cells that are visible to the naked eye.

> Whether it is a training-induced alteration in the chemicals present or a wholesale architectural change in the cell's structure, the effects of exercise on the human begin at the cellular level before they become manifest in outward appearance or performance changes.

Thin filaments are composed of the protein actin held in place by another filamentous protein, nebulin. Actin's configuration is reminiscent of traditional twisted rope, linear with a spiral groove coursing along its length. Actin has two other proteins associated with its structure: troponin and tropomyosin.

Actin and myosin are the primary contractile proteins/myofilaments responsible for muscle contraction. Troponin regulates, through its action on tropomyosin, contractile activity by blocking or facilitating the interactions between actin and myosin. The proteins are organized into repeated sub-units called sarcomeres and form the functional unit of the muscle. A muscle cell is well stocked with myofibrils running along, parallel to, the long axis of the cell. These structural orientations give rise to optical properties, causing the cell to appear striped or striated. Not all muscle cells have a characteristic banding pattern. Smooth muscle cells from the vasculature and gastrointestinal systems are non-striated.

Characteristics of Different Muscle Types

A trip to the grocery store for some beef jerky can provide some excellent perspective on muscle anatomy. Take a really dry piece of jerky and bite/tear it in half (Figure 2). Carefully look at the ripped end of the jerky. The frayed and cotton-candy-like strands are muscle cells or small groups of muscle cells.

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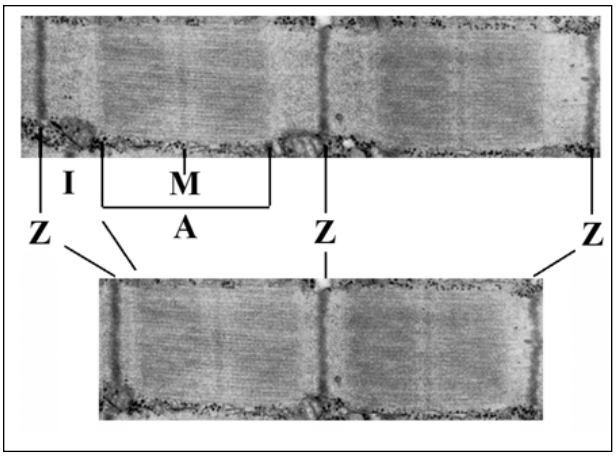

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Figure 3: Sarcomeric anatomy and function. During a muscle contraction, the Z-lines are pulled toward the center of the sarcomere and the I-bands become smaller. This produces movement.

Organelles can be present in cells in varying numbers or absent completely, depending on the function of the cell. A red blood cell has no nucleus, but a muscle cell has a huge number present. This tells us that a red blood cell is not meant to repair or recreate itself. It also tells us that a muscle cell possesses the capability of repair and growth owing to the presence of a large complement of genetic materials. Indeed, this is what happens. As a red blood cell ages or becomes damaged, it is removed from circulation. A damaged muscle cell will use it's genetic power to stimulate the production of repair proteins to re-establish normal function.

Another example of differential presence is again in muscle cells. Most people are familiar with the concept of fast-twitch and slow-twitch muscle fibers. This is a simplistic concept but works well here for illustration. Slow-twitch fibers possess a large number of mitochondria. Fast-twitch do not. This anatomical difference yields a functional difference in that the high numbers of mitochondria in slow-twitch fibers are energetically efficient, and slow-twitch fibers are thus fatigue resistant. Fast-twitch fibers, having few mitochondria, fatigue within a few seconds of maximal contraction.

Fast-twitch fibers are also larger than slow-twitch fibers and thus have more sarcomeric elements. More actin and myosin means a larger force-production capacity. So it should be apparent, even with this short primer in muscle anatomy, that anatomical form dictates physiological function. This theme will be repeated over and over throughout your study of anatomy.

It is very important to note that exercise training can change the anatomical structure of a cell. Whether it is a training-induced alteration in the chemicals present or a wholesale architectural change in the cell's structure, the effects of exercise on the human begin at the cellular level before they become manifest in outward appearance or performance changes.

How the Body Moves

Let's consider how the myofibrils characteristic of muscle cells function to produce movement (the physiology component of this lesson).

The accepted mechanism of muscle contraction is a relatively modern concept, proposed in its most basic form in the 1950s by H.E. Huxley. In his sliding filament theory, the two contractile proteins, actin and myosin, bind to each other intermittently and transiently when neurally stimulated to do so.

It's a fairly easy concept to understand: your brain or a reflex sends a signal out along a motor neuron (a nerve feeding information to a muscle). The neural signal hits the muscle cell, which triggers chemical events inside the cell. Those chemical events yield a binding of actin to myosin, energy gets expended, and myosin changes shape, causing myofibril and cell shortening and a production of force.

Think of actin as a ladder lying on the floor. At the distal end, the last rung of the ladder, is something you want. Think of sitting at the proximal end of the ladder opposite the object you want. How do you get the thing? Using your hands and arms you pull the far end of the ladder, hand over hand and rung by rung, closer to you until finally have the desired object within reach.

In this analogy you have behaved like myosin, cycling your hand contacts and force generation against actin (the ladder) to accomplish movement. Now think of doing this same task in tandem with someone else working with another ladder, pulling their ladder and desired object in the opposite direction. In this orientation you and your partner are behaving like a sarcomere, the basic contractile unit of the muscle cell, pulling the ends of the system towards center. There are approximately 400 sarcomeres for every millimeter of myofibril. The structure of a

sarcomere allows for a cumulative in-series shortening of the length of the entire muscle cell through an energy-dependent mechanism (Figure 3).

A sarcomere is bounded on each end by a Z-line into which actin is anchored. Myosin is anchored in the center of the sarcomere at the M-line and is represented by the A-band. The area between the Z-line and the A-band, the I-band, is variable in width. In a relaxed state the I-band is wide. As the muscle contracts, Z-lines are pulled toward the center and I-bands become smaller.

So the myofibrils, the long chains of sarcomeres that are contained within the muscle cell, generate the force. The force is transferred to adjacent cells by virtue of the connective tissue surrounding each cell. This connective tissue is called the endomysium, and the endomysium surrounding one cell merges with that of its neighboring cells.

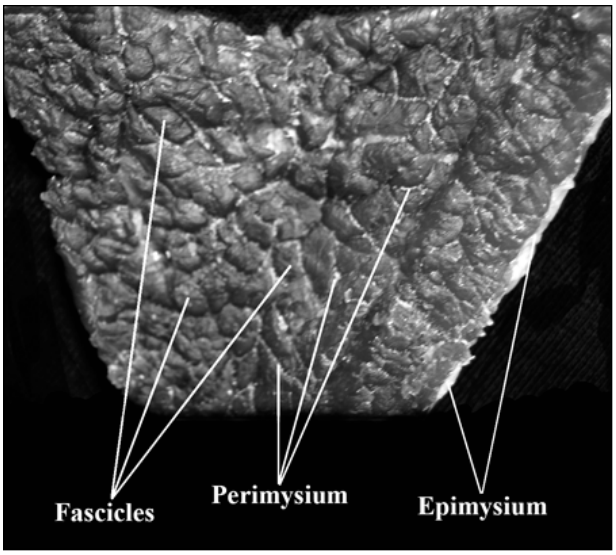
A secondary level of connective tissue structure assists in force transference. Surrounding significant numbers, or bundles, of muscle cells you will find a thicker connective tissue called the perimysium. The perimysium and all of the muscle cells within its boundaries are called a fascicle. A fascicle is easily visible to the naked eye (Figure 4).

There is one more level of connective tissue structure that enables force transference: the epimysium. The epimysium is the connective tissue layer that bounds whole muscle. So each layer of this connective tissue tree is contiguous with the other and culminates in presenting as tendons at the muscle's sites of attachment to bone.

The shortening of sarcomeres results in the shortening of the whole muscle and acts to bring the two bones attached to the muscle closer together. If a muscle shortens, it contracts.

With the exception of the connective tissue surrounding individual muscle cells (the endomysium, not visible to the naked eye), a cross-cut piece of jerky or virtually any steak at the grocery meat counter can demonstrate the organization of connective tissues in the muscle. Bundles of muscle fibers are surrounded by connective tissue (the perimysium) and collectively called fascicles. Bundles of fascicles are bounded by more connective tissue (the epimysium), forming a complete muscle.

A structural variation in the way muscle cells are situated within connective tissue affects the amount of force generated by the muscle (Figures 5A and 5B). "Pennation" refers to the angle at which the muscle cells lie in relation

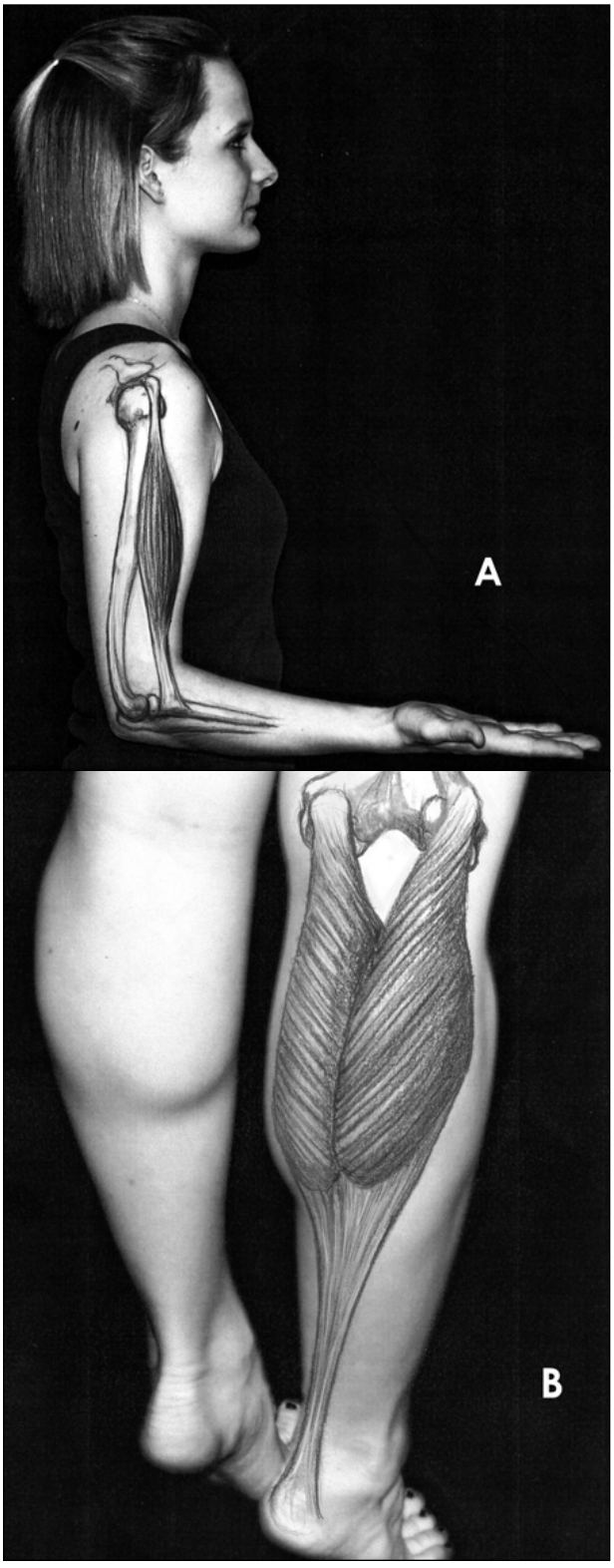


Dr. Lon Kilgore

Figure 4: Connective tissues of the muscle—perimysium and epimysium. These tissues culminate in tendons, which attach to bones and transfer the muscular forces that produce movement about a joint.

to the long axis of the tendon on which they act. When a muscle's fibers run parallel to the long axis of its tendon, the muscle is capable of changing its length greatly and rapidly, although it produces moderate force (directly proportional to the force generated by sarcomeric shortening). A muscle of identical mass to the parallel muscle described above but whose fibers insert into its tendon at 45 degrees experiences amplification in force production. It's a math and physics thing with sines and cosines involved, but at the root of it there are more muscle fibers packed into the same space. This type of muscle orientation will be capable of generating much more force than the parallel muscle, although it will occur over a shorter range of motion and at a lower velocity.

How does this tidbit of anatomical and physiological information help us teach or program exercise? Think of all the calf-exercise gimmicks out there proposing to improve vertical jump or sprint speed. Now think of the multi-headed gastrocnemius muscle (the big one of the calf). It has muscle fibers that are pennate to its tendon (the Achille's or calcaneal tendon) and as such is biased to produce force not velocity (you can't jump slow). Fiber type and mechanical lever issues further limit the contribution of the gastrocnemius to jump height. Placing a



Dr. Lon Kilgore

great deal of training attention on the gastrocs with the intent of increasing jumping performance is likely time misspent.

Movement: From Cells to Sit-ups

A conceptual understanding of the anatomy of muscle contraction makes it obvious that there is much going on within a muscle during contraction. Indeed there is, from individual molecules to the entire muscle. Muscle anatomy forms the structural basis of contraction. From the proteins that produce the force to the level of whole muscle action, a simple understanding of how things are built forms the core of our knowledge of how to change their structure to improve their function. The physiological processes inducing and supporting muscle contraction are numerous, diverse and important to know. Making muscle move requires the involvement of the neural, cardiopulmonary, skeletal and muscular systems, making it an integrated physiological topic for later consideration.

✦

About the Author

Lon Kilgore, PhD, is a professor of kinesiology at Midwestern State University, where he teaches sport and fitness physiology and applied anatomy. He has authored or co-authored several professional exercise textbooks, numerous research articles on the biology of exercise, and many articles that interpret exercise science for the average coach and trainee. His students have become university faculty, high school and university sport coaches, private fitness practitioners, physicians, physical therapists, wellness directors, and U.S. national team coaches in weightlifting and cycling. He has been a member or chair of the Sports Science Committee for U.S.A. Weightlifting for more than a decade, a researcher on the USOC Weightlifting Performance Enhancement Team project, and a member of the Board of Certification for the American Society of Exercise Physiologists.

Figure 5: Muscle pennation.
The biceps brachii (A) are muscles with "parallel" muscle fiber arrangement (parallel to the long axis of the tendon).
A bipennate muscle, such as the gastrocnemius (B), has different sets of muscle fiber angles radiating from a central tendon.

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