Biomechanical Factors in Human Strength

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BIOMECHANICS IS THE STUDY of how the various components of the human musculoskeletal "machine" interact to create movement. Knowledge of biomechanics is important for understanding sports and resistance exercise, providing insight into how body movements are carried out and how forces within the musculoskeletal system produce either beneficial or harmful effects. Such information can facilitate the design of effective and safe resistance training programs.

This article provides a biomechanical perspective on human strength and power. It shows how strength is affected by factors such as anatomical structure, leverage, nervous system control, muscle cross-sectional area, muscle fiber arrangement, muscle length, muscle contraction velocity, body joint angle, joint angular velocity, and body size. It reveals the three-dimensional nature of strength and the importance of the strength-to-mass ratio.

The Musculoskeletal System

The muscles of the body do not act directly to exert force upon the ground or other external objects. Instead, they function by pulling against bones, rotating them about joints to transmit force through the skin to the external environment. Sport and exercise movements mainly involve rotations about the synovial joints such as the knee and elbow, which are characterized by low friction and large range of motion.

While muscles can only pull, not push, muscle pulling forces can be manifested in either pulling or pushing forces against external objects through the system of bony levers.

Joints can be categorized by the number of axes about which rotation occurs. Uniaxial joints such as the elbow operate as hinges, essentially rotating about only one axis. Although the knee is often referred to as a hinge joint, its axis of rotation actually changes throughout the joint range of motion. Biaxial joints, such as the ankle and wrist, allow movement about two perpendicular axes. Multiaxial joints allow movement about all three perpendicular axes that define space and include the shoulder and hip ball-and-socket joints.

In order to bring about movement or generate force against external objects, both ends of a skeletal muscle must be attached via connective tissue to bone. Each of the muscles responsible for the major body movements extends across one or more joints, causing joint rotation when it contracts. A straight-line movement of the hand is effected by rotations about the elbow and shoulder, while a straight-line movement of the foot is effected by rotations about the knee and hip.

There are various ways in which muscles are attached to bone. In fleshy attachments, muscle fibers are directly affixed to the bone. Fibrous attachments, such as tendons, blend into both the muscle sheaths and the connective tissue surrounding the bone. They have additional fibers that extend into the bone itself, making for a very strong union.

Tendons are capable of sustaining forces as high as 12,000 newtons per square centimeter (17,000 lbs per square inch) of cross-sectional area (12). However, they do occasionally sustain injury or even rupture under extreme forces, especially when not properly warmed up and stretched before exercise or when weakened by injection of cortisone (17, 20). There is also some evidence that the use of anabolic steroids can weaken tendons and other connective tissue, predisposing them to injury (19).

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Virtually all body movements involve the action of more than one muscle. The muscle most directly involved in bringing about a movement is called the prime mover or agonist. A muscle that can slow down or stop the movement is called the antagonist. The antagonist assists in joint stabilization and in slowing limb speed toward the end of a fast movement, protecting ligament and cartilage in the joint from sustaining potentially destructive forces.

A muscle is called a synergist when it assists indirectly in a movement. For example, the muscles that stabilize the scapula act as synergists during upper arm movement. Many of the muscles that move the upper arm originate on the scapula. Without the synergists to fixate the scapula, the prime movers would not be effective in moving the upper arm.

Synergists are also needed to control body motion when the prime mover is a muscle that crosses two joints. For example, the rectus femoris is the only muscle of the quadriceps group to cross both the hip and knee, acting to flex the hip and extend the knee when contracting, as during a kick. Rising from a low squat involves both hip and knee extension. If the rectus femoris is to extend the knee during the squat, then hip extensor muscles such as the gluteus maximus must act synergistically to counteract the prime mover's hip flexion action.

## Leverage

Understanding the musculoskeletal system requires a basic knowledge of levers. The following definitions, illustrated in Figure 1, are necessary for understanding leverage:

1. **Lever**: A rigid or semi-rigid structure that can, through rotation about a pivot point, translate movement and force at one point to either greater movement and less force, or greater force and less movement, at another point.

2. **Fulcrum**: The pivot point about which the lever rotates.

3. **Moment arm** (also called force arm, lever arm, or torque arm): The perpendicular distance from the line of action of the force to the fulcrum.

4. **Torque** (also called moment): The tendency of a force to rotate an object about a fulcrum, defined as the magnitude of a force times the length of its moment arm.

5. **Muscle force**: Force generated by biochemical activity which acts to draw the opposite ends of a muscle toward each other.

6. **Resistive force**: Force generated by a source external to the body (e.g., gravity, inertia, friction) which acts contrary to muscle force.

7. **Mechanical advantage**: The ratio of the moment arm through which an applied force acts to that through which a resistive force acts. A mechanical advantage greater than 1.0 means that the applied force is less than the resistive force but produces an equal amount of torque. A mechanical advantage of less than 1.0 is a disadvantage in the usual sense.

Human limbs are operated as levers rotating about body joints; the moment arm through which the muscle force acts is much smaller than the moment arm through which the resistive force acts. That is why muscle forces are extremely high relative to forces exerted by the hands or feet on external objects. For example, in Figure 1, because the resis-
ance moment arm is eight times longer than the muscle moment arm, muscle force must be eight times the resistive force. The extremely high internal forces experienced by muscles and tendons account in large part for injury to these tissues.

Mechanical advantage often changes continuously during real-world activities for reasons such as the following:

1. The knee joint is not a true hinge because the point about which the joint pivots changes continuously throughout the range of motion, affecting the length of the moment arm through which the quadriceps and hamstrings act. The patella, or knee cap, helps to prevent large changes in the mechanical advantage of the quadriceps by keeping the muscle group's tendon from falling in close to the axis of rotation when the knee extends.

2. For movements such as knee and elbow flexion, there is no structure such as the patella to keep the distance from the joint axis of rotation to the tendon's line of action relatively constant. Thus the torque that a given amount of muscle force can produce is lower at the extremes of the joint range of motion, where the tendon falls closer to the axis of rotation.

3. During weightlifting exercise, the moment arm through which the weight acts varies directly with the horizontal distance from the weight to the body joint.

An individual whose tendons are inserted on the bone farther from the joint center should be able to lift heavier weights because muscle force acts through a longer moment arm and thus can produce greater torque around the joint. However, it is important to recognize the tradeoff involved in tendon insertion. The mechanical advantage gained by having tendons insert farther from the joint center is accompanied by a loss of maximum speed because with the tendon inserted farther from the joint center, the muscle has to contract more to make the joint move through a given range of motion.

From another point of view, a given amount of muscle shortening results in a smaller angle of joint movement, which translates into a loss in movement speed. Figure 2a shows that, starting with the joint extended, when a hypothetical muscle shortens by a given amount, the joint rotates by 33°. However, if the muscle were inserted further from the joint center as in Figure 2b, the same amount of muscle shortening would bring about only 24° of joint rotation.

To produce a given joint angular velocity, a muscle inserted farther from the joint center must contract at a higher speed, at which it is less capable of generating force due to the force-velocity relationship of muscle (16) described below. Therefore such a tendon arrangement reduces the muscle's force capability during faster movements.

One can see how some relatively subtle individual differences in structure can result in various advantages and disadvantages. For slow-speed movements, such as in power lifting, tendon insertion farther from the joint than normal can be advantageous, while for athletic activities at high speeds, such as tennis, the arrangement can be disadvantageous.

**Neural Control**

Muscle fibers do not contract individually. Instead they are organized into groups that contract to-
gether. A group of muscle fibers along with the nerve that controls the group is called a motor unit. One muscle is made up of many motor units. Body movements requiring fine control are brought about by motor units that have relatively few muscle fibers, while body movements that are more powerful but don’t require as much fine control are brought about by motor units that contain more muscle fibers.

The nervous system can affect the maximal force output of a muscle by determining which and how many motor units are involved in a muscle contraction (recruitment) and the rate at which the motor units are fired (rate coding) (3). Generally, muscle force is greater when (a) more motor units are involved in a contraction, (b) the motor units are greater in size, or (c) the rate of firing is faster.

Much of the improvement in strength evidenced in the first few weeks of resistance training is attributable to nervous system adaptations rather than muscle hypertrophy (increase in size) (15).

### Muscle Cross-sectional Area

All else being equal, the force a muscle can exert is related to its cross-sectional area rather than to its volume (10). For example, if two athletes of similar percent body fat but different height have the same upper arm circumference, their upper arm muscle cross-sectional areas are about the same. While the taller athlete’s longer muscle makes for greater muscle volume, the upper arm strength of the two athletes should be about the same.

Since body weight is related to volume, the taller athlete weighs more. With the same strength but greater body weight, the taller athlete has less ability to lift and accelerate his or her own body, as in performing calisthenics or gymnastics.

### Muscle Fiber Arrangement

Maximally contracting muscles have been found capable of generating between 16 and 100 newtons of force per square centimeter (23–145 lbs/in.²) of muscle cross-sectional area (1, 6, 7, 13). The wide range can be partially accounted for by the arrangement of fibers within a muscle.

Figure 3 shows various arrangements of muscle fibers. Some examples of muscles incorporating the various fiber arrangements are the rectus abdominis (longitudinal), biceps brachii (fusiform), pectoralis major (radiate), tibialis posterior (unipennate), rectus femoris (bipennate), and deltoids (multipennate) (4, 7).

A pennate muscle is one in which the fibers have a featherlike arrangement. The angle of pennation is defined as the angle between the overall muscle and its fibers; 0° corresponds to no pennation. Few human muscles have pennation angles in excess of 15°. Actually, the angle of pennation does not remain constant for a given muscle but increases as the muscle shortens.

Penetration appears to provide some enhancement of force capability for muscle contracting at high speed, particularly at the extremes of the range of muscle motion. Yet it has been shown that penetration can be somewhat disadvantageous for generating eccentric, isometric, or low-speed concentric force (18). While there is a tradeoff associated with penetration, and it is not the most advantageous arrangement for all muscles, many skeletal muscles are pennate (4).

### Muscle Length

Muscle force is generated when cross-bridges are formed between actin and myosin contractile muscle filaments (Figure 4). When a muscle is at its resting length, a maximal number of cross-bridge sites are available between the filaments. When the muscle is shorter or longer than its resting length, however, there are less available sites. Thus the muscle is able to generate the most force around its resting length, and less force when it is in an elongated or shortened state.

### Joint Angle

Because almost all body movements, even those occurring in a straight line, take place through joint rotations, the forces that
muscles produce must be manifested as torques. The pattern of maximal muscle torque through the full range of joint motion is not the same as the pattern of maximal muscle force powering the movement.

There are three reasons for this: (a) Due to changes in pivot point location and tendon position throughout the movement, the moment arm through which the muscle acts can vary. (b) Usually two or more muscles act together to cause movement about a given body joint; at any particular joint angle, the different muscles are at different points in their force versus length curves. (c) The length of a muscle that crosses two body joints (e.g., biceps, triceps, rectus femoris, hamstrings) is affected by both joint angles.

Figure 4. Muscle force is generated when cross-bridges are formed between actin and myosin contractile muscle filaments. More cross-bridge sites are available when a muscle is at its resting length than when it is shorter or longer, allowing more force to be developed.

Figure 5 shows torque versus joint angle curves for knee extension and flexion. It is evident that the patterns of torque capability versus joint angle differ among body movements. For a given body movement, curves for higher contraction speeds are lower in amplitude but similar in shape to those for lower contraction speeds.

Muscle Contraction Velocity

Classic experiments by A.V. Hill on isolated animal muscle have shown that muscles produce less force as the velocity of contraction increases (9). The relationship is not linear; the decline in force capability is steepest over the lower movement speed range.

Because most skeletal muscle forces act to cause rotation about joints, the muscle force-velocity relationship results in a drop in torque capability as speed of joint rotation increases. However, there are some differences in shape between curves of muscle force versus contraction velocity and muscle torque versus joint angular velocity due to joint geometry.

Joint geometry also explains why, during isokinetic exercise, joint angle changes at a constant rate while the muscle length changes at a variable rate. In Figure 6, for example, as the arm starts flexing, the muscle contracts only a small amount for a 30° change in elbow angle; as the elbow flexes through the middle of its range of motion, much more muscle shortening is required to produce the same change in elbow angle.

Because "contraction" means shortening, the term does not accurately describe isometric or eccentric exercise; the term "action" should be used instead. There are three basic types of muscle action, during which contractile force acts to pull the muscle's ends toward each other: (a) concentric, when the muscle shortens because the contractile force is
Figure 6 During isokinetic exercise, as the arm starts flexing, the muscle contracts only a small amount for a 30° change in elbow angle. As the elbow flexes through the midrange, however, more muscle shortening is required to produce the same change in angle; thus the muscle must contract faster.

![Graph showing the relationship between joint angular velocity (deg/sec) and % max.

Figure 7 Maximal torque as a function of joint angular velocity. As concentric contraction speed increases (from center toward right side of graph), torque capability declines. As eccentric speed increases (from center toward left side of graph), torque capability increases, then declines.

3-D Strength Relationship

It is important to note that each torque versus joint angle curve depicted in Figure 5 resulted from testing at one angular velocity, and the torque versus angular velocity curve depicted in Figure 7 resulted from testing at one joint angle.

A more comprehensive view of strength can be obtained when maximal torque capability is shown as a function of both joint angle and angular velocity in a three-dimensional plot (Figure 8). Such a depiction allows recognition of relative force capability at various combinations of joint angle and angular velocity for a particular body movement.

Strength-to-Mass Ratio

In sport activities such as sprinting or jumping, strength-to-mass ratio is critical. According to Newton’s second law (14),

\[ \text{Force} = \text{mass} \times \text{acceleration} \]  
\[ \text{acceleration} = \frac{\text{force}}{\text{mass}} \]

Thus the strength-to-mass ratio directly reflects the ability to accelerate the body. If, after training, an athlete increases body mass by 15% but increases force capability by only 10%, then the strength-to-mass ratio is reduced along with the ability to accelerate the body. A runner or jumper may benefit by experimenting with muscle mass to determine the highest strength-to-mass ratio and concomitant best performance.

In sports involving weight classification, strength-to-mass ratio is also extremely important. If all competitors have the same body mass, the athlete with the highest strength-to-mass ratio is the strongest and has a decided advantage.

It is normal for the strength-to-mass ratio of larger athletes to be lower than that for smaller athletes (2). Trial and error can help an athlete determine the weight category in which his/her strength is highest relative to other athletes in the weight class. Once an athlete finds his/her most competitive weight class, the
object is to become as strong as possible without exceeding the class weight limit.

Workouts can be tailored to improve strength-to-mass ratio. Body-building routines are to be avoided because they generally result in body mass increases that are proportionally greater than strength increases, thereby reducing strength-to-mass ratio. Strength oriented routines are more appropriate, with emphasis on heavier weights, less repetitions, and longer rest periods between sets of an exercise.

Performing alternating sets of exercise for two or three different body movements (e.g., A-B-A-B-A-B or A-B-C-A-B-C-A-B-C), as in the Multiple Mini-Circuit exercise routine (5), is a good way to allow for adequate rest intervals between sets of the same exercise without excessively slowing down the workout. It may be necessary to cut calories to prevent gain in body mass.

## Body Size

It has long been observed that, all else being equal, smaller athletes are stronger "pound for pound" than larger athletes. The reason is that a muscle's maximal contractile force is roughly proportional to its cross-sectional area, while its mass is proportional to its volume.

Assuming that body segments are largely cylindrical, then area is related to the square and volume is related to the cube of linear body dimensions. Therefore, all else being equal, as body size increases, body weight increases more rapidly than does muscle strength. Given constant body proportions, the smaller athlete thus has a higher strength-to-mass ratio than does the larger athlete (2).

There has always been interest in comparing the performances of lifters in different weight categories. The most obvious method for doing so is to divide the weight lifted by the athlete's body weight. However, such an adjustment is biased against larger athletes because it does not take into account the expected drop in strength-to-mass ratio with increasing body size.

Various formulas have been derived to allow for a more equitable comparison of lifts. In the classical formula, the lift is divided by body weight to the two-thirds power, thus accounting for the muscle cross-sectional area versus body mass relationship discussed above.

Other formulas have since been developed because the classical formula seemed to favor athletes of middle body weight over both lighter and heavier athletes (8). However, the classical formula's determination that the performances of medium-weight lifters are usually the best may indeed be unbiased; one would expect the weight category with the largest number of competitors to produce the best performers.

In some sporting activities, body size may be more important than strength-to-mass ratio. In football, it is desirable for an offensive lineman to be difficult to push aside. According to Newton's equations above, it takes more force to accelerate a greater mass, thus it is more difficult to move the heavier player. By the same token, it is more difficult to divert or stop a more massive offensive running back.

However, there is always a tradeoff. Any player gaining weight reaches a point at which reduced strength-to-mass ratio lessens the athlete's ability to accelerate his/her own body—to the extent of overriding any advantage due to increased body mass.

An effective resistance training program can raise the body mass...
at which performance begins to decline, thus producing a bigger and better player in sports in which body weight is important. It is not unusual for players to get bigger by excessive caloric consumption, however, not realizing that most of the weight gain is actually fat. Athletes and coaches alike must be attuned to the balance, for each individual, between body mass and the strength-to-mass ratio.

- Conclusions

Various biomechanical factors that relate to the application of force during resistance training and sports have been discussed in this article. It is hoped that such knowledge will enable strength and conditioning practitioners to apply biomechanical principles to the design of resistance exercise programs.

A basic foundation in exercise physiology and biomechanics, along with practical strength and conditioning experience, provides the soundest basis for prescribing exercise programs suited to the specific needs of various kinds of athletes and others who engage in resistance training for enhancing performance and health.

- References


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