Resistance Training Modes: A Biomechanical Perspective

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Over the past several years there has been a great increase in the variety of resistance exercise devices on the market. While some traditional strength and conditioning professionals advocate only the use of free weights, most others recommend the use of at least some exercise machines. A recent survey commissioned by the NSCA through its certification agency showed that a great majority of NSCA Certified Strength and Conditioning Specialists support the use of machines in conjunction with free weights for novice level resistance training programs.

Although the survey didn’t ask about the use of machines in more advanced programs, there seems to be widespread support for using machines in resistance exercise programs at all levels, mainly for providing resistance to body movements that are difficult to exercise with free weights (e.g., pull-down, leg adduction and abduction, knee flexion, trunk rotation).

Because the strength and conditioning professional can choose among a wide variety of exercise machines, the process of finding the best machine for a specific purpose is difficult. This article is intended to aid in the search by providing a biomechanical perspective on various kinds of resistance exercise machines according to the source of resistance; it does not compare specific machine brands.

Sources of Resistance to Muscle Contraction

The most common sources of resistance for strength training exercises are gravity, inertia, friction, fluid resistance, and elasticity. This section provides information on the force and power required to overcome these various forms of resistance.

Gravity

General principles. The downward force on an object due to gravity, otherwise called the object’s weight, is equal to the object’s mass times the local acceleration of gravity.

\[ F_g = m \cdot a_g \]  

where: \( F_g \) = force due to gravity (same as the object’s weight); \( m \) = the object’s mass; and \( a_g \) = the local acceleration of gravity (Table 1). In the international system of units, force is in newtons, mass is in kilograms, and acceleration is in meters per second squared.

The farther an object is from the earth’s center, the less it weighs. Because the earth rotates and bulges out at the equator, objects weigh less near the equator than farther north or south. Altitude relative to sea level causes a similar but much smaller effect. The acceleration of gravity can vary as much as 1% on the earth’s surface, enough to affect world records in lifting and jumping. One can expect to lift a greater mass and jump higher near the equator. To get an accurate barbell weight, a calibrated spring or electronic scale must be used. A balance scale determines only the object’s mass; its weight can be calculated using Equation 1.

The microgravity conditions in space reduce the resistive force experienced by the muscles, re-
sulting in both muscle atrophy (1) and loss of bone mineralization, particularly in the weight-bearing bones (10). Exercise programs aboard spacecraft have been implemented, using devices that provide resistance other than gravitational force, in an effort to reduce such losses (1). Because gravitational force in space is so low, weights are not effective for exercise. The design of resistance exercise programs to maintain muscle mass and strength in space is of great concern.

Popular terminology for weight and mass is often incorrect. For example, some weight plates are labeled in pounds. The pound is a unit of force, not mass. In actuality, only the mass of a weight plate stays constant while its weight varies according to the local acceleration of gravity. The kilogram designation on a weight plate refers to its mass. It is not correct to say that an object weighs a certain number of kilograms, since weight refers to force, not mass.

**Applications to resistance training.** The gravitational force on an object always acts downward. Since, by definition, the moment arm by which a force produces torque is perpendicular to the line of action of the force, the moment arm of a weight is always horizontal. Thus torque due to an object’s weight is the product of the weight and the horizontal distance from the weight to the pivot point.

During a lift, although the weight does not change, its horizontal distance from a given joint axis changes constantly. When the weight is horizontally closer to the joint, it exerts less resistive torque, but when it is horizontally farther from a joint it exerts more resistive torque. For example, in an arm curl (Figure 1) the horizontal distance from the elbow to the barbell is greatest when the forearm is horizontal. The moment arm decreases as the forearm rotates either upward or downward away from the horizontal, decreasing the resistive torque due to the weight. When the weight is directly above or below the elbow pivot point, there is no resistive torque due to the weight.

Lifting technique can affect the resistive torque pattern during a lift. In the squat for example, a more forward inclination of the trunk brings the weight horizontally closer to the knee, thus reducing resistive torque about the knee which the quadriceps must counteract. At the same time the weight is horizontally farther from the hip, increasing the resistive torque about the hip which the gluteus and hamstring muscles must counteract.

Lifting technique can thus be modified to shift stress among muscle groups. Competitive lifters generally adjust their lifting techniques to shift more of the lifting effort to those muscles that are relatively strong. While gen-

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**Table 1**

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Acceleration due to gravity (m/s²)</th>
<th>Sample location</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>9.780</td>
<td>Nairobi, Kenya</td>
</tr>
<tr>
<td>10°</td>
<td>9.782</td>
<td>Caracas, Venezuela</td>
</tr>
<tr>
<td>20°</td>
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</tr>
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<td>30°</td>
<td>9.793</td>
<td>Houston, Texas</td>
</tr>
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<td>40°</td>
<td>9.802</td>
<td>Denver, Colorado</td>
</tr>
<tr>
<td>50°</td>
<td>9.811</td>
<td>Bonn, Germany</td>
</tr>
<tr>
<td>60°</td>
<td>9.819</td>
<td>Anchorage, Alaska</td>
</tr>
</tbody>
</table>

*Note: A more complete table can be found in the *Handbook of Chemistry and Physics*, Cleveland OH: CRC Press.*
eral lifting principles apply to everyone, the details of optimal lifting technique vary among individuals.

**Weight stack machines.** As with free weights, gravity is the source of resistance for weight stack machines. However, through pulleys, cams, cables, and gears, the machines provide increased control over the direction and pattern of resistance. Both free weights and stack machines have advantages as well as disadvantages. Some advantages of the stack machine include:

- **Safety:** The likelihood of injury through being hit by, tripping over, or being trapped under a weight is reduced. It requires less skill to maintain control of a weight stack than a free weight.

- **Design flexibility:** Machines can be designed to provide resistance to body movements that are difficult to resist with free weights (e.g., hip adduction and abduction). To some extent, the pattern of resistance can be engineered into a machine.

- **Ease of use:** It is quicker and easier to select a weight by inserting a pin in a stack than by mounting plates on a bar.

Advantages of free weights include:

- **Whole-body training:** Free weight exercises are often performed in the standing position with the weight supported by the entire body, taxing a larger portion of the body's musculature than machine exercises do. Such weight-bearing exercise promotes bone mineralization, helping to prevent osteoporosis in later life (8). The movement of a free weight is constrained by the lifter rather than by a machine, requiring muscles to work in stabilization as well as support. "Structural" lifts such as cleans and snatches are particularly useful in providing training stimulus for a major portion of the body's musculature.

- **Simulation of real-life activities:** The lifting and acceleration of objects comprise a major part of sports and other physically demanding activities. While machines tend to isolate single muscle groups, the lifting of free weights involves the more natural coordination of several muscle groups.

Nautilus Sports/Medical Industries popularized the concept of engineering resistive torque through the range of joint motion into an exercise machine by the use of a cam of variable radius that changes the length of the moment arm through which the weight stack acts (Figure 2).

The rationale was to provide more resistance in the range of motion where the muscles could exert greater torque, and less resistance where the muscles could apply less torque. However, in order for the system to work as planned, the lifter has to move at a constant slow angular velocity, which is difficult to do consistently. Also, current cam-based machines don't necessarily match normal human torque capability patterns (3, 5).

**Inertia**

In addition to gravitational force, a barbell or weight stack, when accelerated, exerts inertial force on the lifter. While the force of gravity acts only downward, inertial force can act in any direction. The downward force on a lifter equals the bar's weight plus its mass times its upward acceleration. Horizontal force on a lifter equals the bar's mass times its horizontal acceleration.

Deceleration, or slowing down

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**Figure 2** In cam-based weight stack machines the moment arm of the weights (horizontal distance from the cable to the cam pivot point) varies during the exercise movement. When the cam is rotated as shown, the resistive torque increases in proportion to the moment arm increase from M₁ to M₂.
of a weight, also called negative acceleration, requires net force in the opposite direction to which the weight is moving. For a weight moving upward, the lifter can reduce upward force on the bar and let the force of gravity decelerate the weight. If the weight is moving horizontally, as at the top of a standing curl, the lifter must exert force in the opposite direction to which the weight is moving in order to decelerate it. If the weight is moving downward when being lowered, the lifter must exert upward force greater than the weight in order to decelerate it, unless the weight is allowed to fall to the floor.

... weight lifting exercises involving acceleration probably produce desirable neuromuscular training effects...

Although acceleration changes the nature of an exercise and makes resistance patterns less predictable, acceleration in lifting should not be considered undesirable. Because acceleration is very much characteristic of natural movements in sports and daily life, weight lifting exercises involving acceleration probably produce desirable neuromuscular training effects (9). Olympic-style lifting exercises such as the snatch and the clean and jerk involve high accelerations of heavy weights (2).

All lifts involve some acceleration at the beginning to bring the bar from a zero to an upward velocity, and some deceleration near the top of the lift to bring the bar's velocity back to zero. With this acceleration pattern, the agonist muscles receive resistance in excess of bar weight early in the range of motion, but resistance less than bar weight toward the end of the range of motion (6).

The lifter decelerates the bar by either (a) reducing upward force on the bar to below bar weight in order to let some or all of the bar's weight decelerate it, or (b) pushing down against the bar using the antagonist muscles. In either case, the deceleration has the effect of providing less resistance to the agonist muscles late in the range of motion.

For a given weight, compared to a slow lift with minimal acceleration, a lift involving higher acceleration ("explosive lift") provides greater resistance to muscles involved early in the lift and less resistance to the muscles involved toward the end of the lift. However, since heavier weights can be handled in an accelerative lift than in the same lift performed slowly, this allows all muscles involved in the lift to attain near maximal resistance. During a heavy snatch lift for example, the strong leg and back muscles accelerate the bar vertically to a high enough velocity so that even though the weaker upper body muscles cannot exert vertical force equal to the bar's weight, the bar continues to travel upward until the force of gravity decelerates the bar to zero velocity at the top of the lift.

**Friction**

Friction is the resistive force encountered while attempting to move two contacting surfaces relative to each other. Exercise devices that use friction as the main source of resistance include belt or brake-pad resisted cycle ergometers and some wrist-curl devices, among others. For such devices,

\[ F_R = k \cdot F_N \]  

where: \( F_R \) = resistive force; \( k \) = a coefficient of friction for the two substances in contact; and \( F_N \) = the normal force, which is perpendicular to the contact surface and presses the objects against each other.

The coefficients of friction for initiating and maintaining movement are different. All else being equal, it takes more force to initiate movement between two substances in contact than to maintain previously initiated movement. Thus, a friction resisted exercise device requires a relatively high force to initiate movement, and a relatively constant force after movement has begun, regardless of movement speed.

**Fluid Resistance**

The resistive force encountered by an object moving through a fluid (liquid or gas), or by a fluid moving past or around an object or through an orifice, is called fluid resistance. It is a major factor in sports activities such as swimming, golf, sprint running, discus throwing, and baseball pitching. It has become important in resistance training with the advent of hydraulic (liquid) and pneumatic (gas) exercise machines, and with the increased popularity of swimming pool exercise routines, particularly among older people, pregnant women, and physical therapy patients.

The two sources of fluid resistance are surface drag, which results from friction of a fluid passing along the surface of an object, and form drag, which results from the way in which a fluid presses against the front or rear of an object passing through it. Cross-sectional (frontal) area has a major effect on form drag.

Fluid resisted exercise machines most often use cylinders in which a piston forces fluid
through an orifice as the exercise movement is performed. The resistive force is greater when (a) the piston is pushed faster, (b) the orifice is smaller, or (c) the fluid is more viscous. All else being equal, resistance is roughly proportional to the velocity of piston movement (4):

\[ F_R = k \cdot v \]  

(3)

where: \( F_R \) = resistive force; \( k \) = a constant that reflects the physical characteristics of the cylinder and piston, the viscosity of the fluid, and the number, size, and shape of the orifices; and \( v \) = piston velocity relative to the cylinder.

Because they provide resistance that increases with speed, fluid cylinders allow rapid acceleration early in the exercise movement, and little acceleration after higher speed is reached. Movement speed is thus kept within an intermediate range. However, while such machines somewhat limit changes in velocity, they are not isokinetic (constant speed), as is often claimed. Some of the machines have adjustment knobs that allow the orifice size to be changed. A larger orifice allows a higher movement speed to be reached before the fluid resistive force curtails the ability to accelerate.

Fluid resisted machines do not provide an eccentric exercise phase. With a free weight, a muscle group acts concentrically while raising the weight and eccentrically while lowering it. With fluid resisted machines, a muscle group acts concentrically while performing the primary exercise movement, and the antagonist muscle group acts concentrically while returning to the starting position.

Thus, while free weights or weight machines involve alternate concentric and eccentric actions of the same muscle group with little or no rest in between, fluid resisted machines involve alternate concentric actions of antagonistic muscle groups; each muscle group rests while its antagonist works.

These factors would lessen the effectiveness of fluid resisted machines if either the eccentric phase of exercise or the maintaining of muscle tension over several seconds is important for strength gains. It is also likely that such exercise does not provide optimal training for the many sports movements that involve eccentric muscle actions such as running, jumping, or throwing.

![Based on these considerations, jumping with a weighted belt or vest is probably more effective...](image)

**Elasticity**

A number of exercise devices, particularly those designed for home use, have elastic components such as springs or bands as their source of resistance. The resistance provided by a standard elastic component is proportional to the distance it is stretched:

\[ F_R = k \cdot x \]  

(4)

where: \( F_R \) = resistive force; \( k \) = a constant that reflects the physical characteristics of the elastic component; and \( x \) = the distance the elastic component is stretched beyond its resting length.

The most obvious characteristic of elastic resistance is that the more the elastic component is stretched, the greater the resistance. The problem with devices using such resistance is that every exercise movement begins with low resistance and ends with high resistance. This is contrary to the force capability patterns of virtually all human muscle groups, which show substantial dropoff of force capability toward the end of the range of motion.

Another problem with elasticity resisted machines is that adjustability of resistance is usually limited by the number of bands that can be affixed to the device. An effective resistance exercise device must incorporate enough variation in resistive force so that the number of repetitions the trainee can perform is kept within the optimal range.

Some products provide resistance to vertical jumping with elastic bands as a means of developing jumping power. However, the elastic bands provide little resistance early in the jump, when the large muscles exert great force. The bands provide the greatest resistance while the jumper is in the air, where they serve mainly to pull the jumper back to the ground rather than to resist the muscles. Based on these considerations, jumping with a weighted belt or vest is probably more effective for developing jumping power.

**Electronically Controlled Devices**

Various resistance training devices are electronically controlled. The actual source of resistance may be one of those described above, or a motor, pump, or electromagnetic device. The distinguishing characteristic of such machines is that they can regulate the degree of resistance during an exercise movement through feedback and control technology. For example, isokinetic dynamometers match resistive force to muscle force in order to maintain constant joint angular velocity. Some such devices allow eccentric exercise as well. Other machines con-
trol parameters such as power output and acceleration.

Given the great variety of electronically controlled exercise machines, it is difficult to generalize about them; each such device must be evaluated individually. However, they are usually much more expensive than other exercise apparatus, and as yet show little evidence of providing superior training stimuli.

**Power Output During Resistance Exercise**

**Weight lifting exercise.** Since work equals force times distance, it takes the same net work to lift a particular weight a given distance, no matter how fast the weight is lifted. However, because power equals work per unit time, when the weight is lifted faster, the average power is higher. Peak power can be very high during accelerative weight lifting. While the force capability of muscle declines with increasing speed of contraction (Figure 3), muscle power capability increases at least until speed surpasses the intermediate range (7).

**Friction resisted exercise.** Since the coefficient of friction does not change with the speed of sliding, then the resistive force of a friction resisted device stays constant regardless of the movement speed. Power output is then directly proportional to the speed of movement.

**Fluid resisted exercise.** For fluid resisted exercise, as velocity of movement increases, the resistive force increases proportionately. Since power is the product of force and velocity, for a given resistance setting the power output is related to the square of velocity for such machines. Because the power output requirement increases so rapidly with movement speed, maximum velocity on these devices is limited.

**Elasticity resisted exercises.** Because resistance is proportional to the distance the elastic component is stretched, these exercises are always easy to perform early in the movement and difficult at the end. If the exercise movement is performed at a constant velocity, the power output is highest late in the movement where resistive force is greatest. As with the other forms of exercise, average power output increases when the exercise is performed faster.

**Electronically controlled exercise.** For rotational devices, power is the product of torque and angular velocity (rotational speed). Thus for an isokinetic device, which moves at an operator-select constant speed no matter how much torque is exerted on the machine, power output during a repetition at a particular speed setting is directly proportional to the instantaneous torque exerted.

To obtain a record of power output during the exercise, each torque data point is multiplied by the angular velocity at which the machine is set. To obtain power in watts, torque must be in newton meters and velocity must be in radians per second (useful conversion factors: foot-lbs = 1.356 foot-lbs × 1.01745 = rad/s). The torque and power output curves are identical in shape.

Some electronically controlled exercise machines can be set to operate at constant power output, no matter how the speed of movement varies. The machines accomplish this by constantly monitoring angular velocity and immediately adjusting the resistive force to keep the product of force and velocity constant.

**Negative power.** Because power equals the product of force and velocity, when force is exerted on a weight opposite in direction to that in which the weight is moving, calculated power has a negative sign. Such “negative power” occurs during eccentric muscle activity, such as lowering a weight or decelerating at the end of a rapid movement.

Strictly speaking, there is no such thing as negative work or power. The term “negative work” really refers to work performed on, rather than by, a muscle. When a weight is lifted, muscles perform work on the weight, which increases its potential energy. When the weight is lowered, the potential energy of the weight is used to perform an amount of work on the lifter equal to the work the lifter performed to raise the weight.
Thus, during a set of weight lifting repetitions, rather than the lifter alternately performing positive and negative work, the lifter and weight alternately perform work on each other. The rate at which the repetitions are performed determines the power output.

## Conclusions

Knowledge of how various types of exercise machines provide resistance to body movements can assist the strength and conditioning professional in selecting the appropriate machines for specific purposes. Knowledge of how the different forms of resistance tax the body can aid in tailoring programs to suit the specific needs of individual athletes and others who engage in resistance training to enhance physical performance.

## References


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