the CrossFit JOURNAL ARTICLES

Forcing the Issue

If movement is the product of unbalanced forces across a joint, what does that mean for traditional agonist-antagonist strength ratios? Dr. Lon Kilgore believes training to conform to hypothetical ratios is impractical and will not result in greater functional fitness.

Dr. Lon Kilgore

Staff/CrossFit Journal

"I find your lack of faith disturbing."

And then squoosh—Force choke! Silent, brutal, indefensible. In one dramatic squeeze of a fist, Darth Vader redefined the popular notion of what The Force was. Albeit a really cool mystical entity, The Force in application still falls under the same basic laws of physics and forces that we mere mortals are resigned to live under.

The first order of business here is to define what a force is. A force is simply a phenomenon that can cause an object to move or accelerate. A force, by definition, has a magnitude (how big the force is) and a direction (which way it is pushing or pulling), making it a vector quantity. Vader's Force choke indeed had a magnitude—large enough to crush a human trachea—and it had a direction. Let's assume the Force choke acted like invisible fingers being squeezed toward the heel of the hand. It's fairly amazing that Isaac Newton had described the physical realities of the mythical forces in the *Star Wars* universe by 1687. Force generation and application is how we move our bodies. The rules surrounding forces and their application have been known for centuries.

In modern physics we can precisely quantify forces in a variety of units (newtons, dynes, kiloponds, pound-force, or foot-pounds), and we can determine in which direction the force is acting. This quantifiability makes force measurement an attractive means of assessing efficient human movement and fitness level, and it even forms the basis of many sports.

The second order of business, because we now know what a force is, is to examine what types of forces are relevant to the study of exercise anatomy and physiology. The type of force and its method of application to the body are extremely germane to understanding how the body moves during exercise, and that understanding proves useful in knowing how to coach movement. Different types of forces act on human anatomy in different and specific manners. Conversely, the human body is constructed to accommodate these forces and to adapt to changes in the nature of their application to ensure survival. Forces acting on the body thus test the limits of existing anatomy while simultaneously driving changes in anatomy.

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When rising out of a squat, traditional wisdom holds that the hamstrings are antagonists to the quads. More correctly, the hamstrings are agonists working to achieve hip extension.

Courtesy of Dr. Lon Kilgore

FIGURE 1: Compression occurs when the body is between an immobile surface and a load attempting to move toward the immobile surface (as shown here), or when the body is in between two loads moving in opposite directions.

FIGURE 2: Tension occurs when gravity acts to pull a suspended body toward the ground (as shown here), or when two loads moving are attempting to move in opposite directions and place a stretch on the body or a body segment.

We can divide the basic types of exercise-related forces as such: compression, tension, torsion and shear.

Compression

If you put a barbell on someone's shoulders, gravity is going to pull the weight toward the ground with a force that is applied along the long axis of the body. In other words, the body is being squished between the weight and the earth. It's a good thing for us that the body is built precisely to tolerate huge compressive forces. After all, supportive bones such as the vertebrae have similar compression resistance to oak structural beams. It is relevant to note here that in healthy trainees, compression of the skeleton rarely leads to structural failure (things breaking). Paul Anderson stood up with over 6,000 lb. on his shoulders. At age 70, Bill Clark did a hip lift with in excess of 1,000 lb. Both are huge compressive forces that produced no anatomical damage.

Proper exercise technique in the face of large compressive forces prevents injury because it allows bones to support the weight, not the less rigid muscles, tendons and ligaments around joints. Obviously, these latter structures contribute, but proper alignment of skeletal elements during exercise allows distribution of compressive forces to those structures that are most resistant and thus prevents orthopedic problems.

Bone-on-bone movement provides more effective force transfer as an added perk.

When done progressively, exercises that possess compressive characteristics develop additional tolerance to compressive force. Exercises with a compressive nature, when done for months to years, stimulate bones to add new mineral content, thus reinforcing the bones and making them even more resistant to fracture.

Tension

The opposite of compression is tension. If someone hangs on a high bar, gravity is going to act on the body by attempting to pull it down to the ground. The grip on the high bar prevents this from occurring, but the downward force along the long axis of the body remains. This is tension. You can think of tension as a stretching force. Adding weight to the system (weights on a hip belt and chain, for example) is one way to increase tension, but adding movement to the system can also increase tension. In the performance of a back hand-swing on a gymnastics high bar, a child can experience a stretching force along the long axis of the body of nearly six times gravity (6 G).

Again, the human body is built to handle application of such linear forces. Our ligaments represent a safeguard, whose engagement represents the limit of space between the bones comprising a joint (exceeding that limit represents ligamentous injury). Vertebral ligaments, once engaged, can stretch about 20 mm before disruption, and a single intervertebral joint will withstand about 224 lb. of tension before failure. Note that this value is from a cadaver study and thus underestimates the force required to disrupt a living joint by about 25 percent. The value also represents an unresisted load, whereas in the living body the vertebral musculature would produce a counterforce that would make the actual force required to produce an injury significantly larger. Regular progressive performance of exercises that produce tension drives gains in tolerance as the loaded ligaments become stronger and thicker. More importantly, the musculature that counters the effects of tension becomes stronger, more enduring and more effective in maintaining joint integrity.

Torsion

If we put a wrench on a nut and then pull on the wrench, the force is applied to the nut in a rotational manner. We can call it torsion or torque (ever heard of a torque wrench?). The same thing occurs in most instances during human movement. We can induce torsion on the vertebral column simply by selectively contracting our own muscles to move our shoulders left or right. Torsion is a normal part of human activities, and inclusion of torsional exercises or exercises that develop the ability to produce or resist torsion is an appropriate training strategy. We need to prepare our bodies beyond producing and resisting linear movement.

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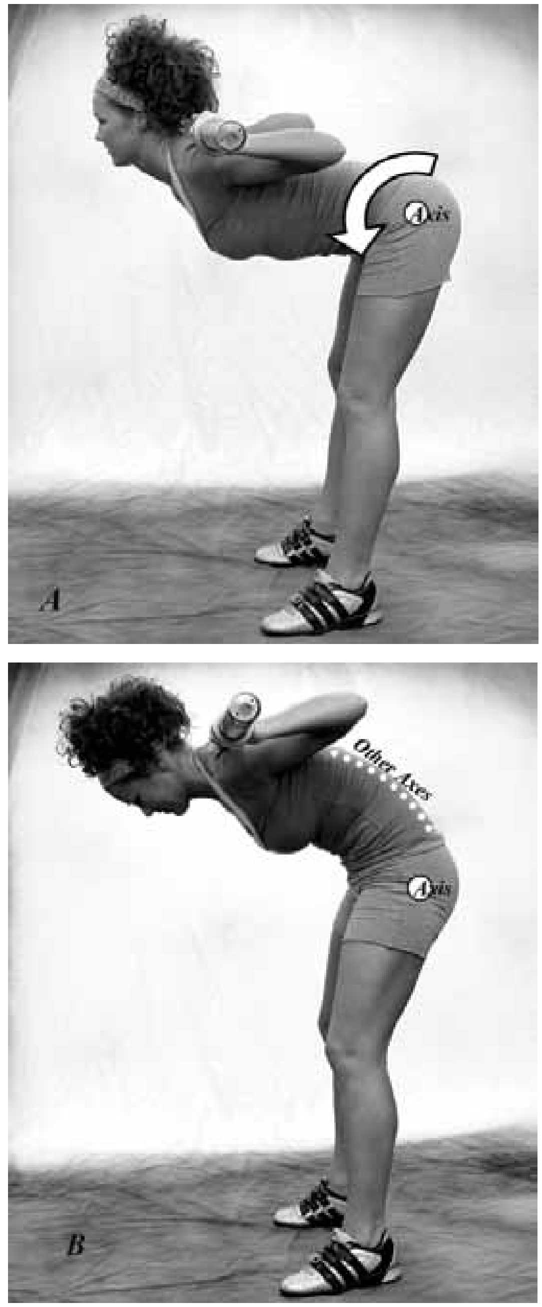
In many instances we can be recipients of involuntary torsion. A gut wrench in wrestling places a large amount of torsional stress on an opponent with the express intent of forcing them to rotate their body to expose their shoulders to the mat. Torsion applied to joints not designed to move in a rotational manner is a problem. This is a rather common problem in plant-and-twist sports such as basketball, soccer (football) and football (American), where we see a large number of ligamentous knee injuries from rotating the femur on top of an immobile tibia. It may not seem intuitive, but comprehensive strengthening of the knee musculature has been shown in many, many studies to aid in reducing the frequency of this type of injury, most likely due to a stronger set of muscles keeping the joint within its normal ligamental limits.

For precision here we need to acknowledge that the preceding is a conceptual presentation. The nut described above rotates on an axis, and although the force applied to the nut through the wrench produces rotation, the more accurate term is "moment." The distance between the



Courtesy of Dr. Lon Kilgore

FIGURES 3A AND 3B:
A load placed on the body that applies a rotational force is torsion or torque. In Figure 3a, during the good morning exercise the bar is pulled down by gravity and torsion occurs around the hip, the axis of rotation (or fulcrum of the system). If the load placed on the vertebral column is greater than the vertebral extensors can maintain in proper position, there will be a series of induced moments around which individual vertebrae will rotate, thus allowing bending of the vertebral column (Figure 3b).

point of resistance (the nut) and the point of force application (the hand on the wrench) is called a moment arm. The longer the moment arm, the larger the moment at the axis of rotation. This will be useful information when we discuss levers later in this series of essays.

Shear

If one segment of the body has force applied to it in one direction and an adjacent segment has force applied to it in an opposite direction, a shear force is present. The presence of shear is not particularly dangerous as long as the musculature involved is developed to the point that it is strong enough to prevent movement of the adjacent segments in opposite directions.

Unresisted vertebral shear could pose significant problems, so exercises directed at development of the musculature that accomplishes vertebral column stabilization are important to fitness, sport performance and avoidance of orthopedic injury. However, even when the shear force is unresisted, it takes about 336 lb. of pressure across one intervertebral joint to induce failure and bone translation (linear sliding) in cadaver studies. Again, in the living human it requires a greater unresisted force to induce joint failure, and when muscular contractions produce stabilizing forces, the amount of force required for failure would be even higher.

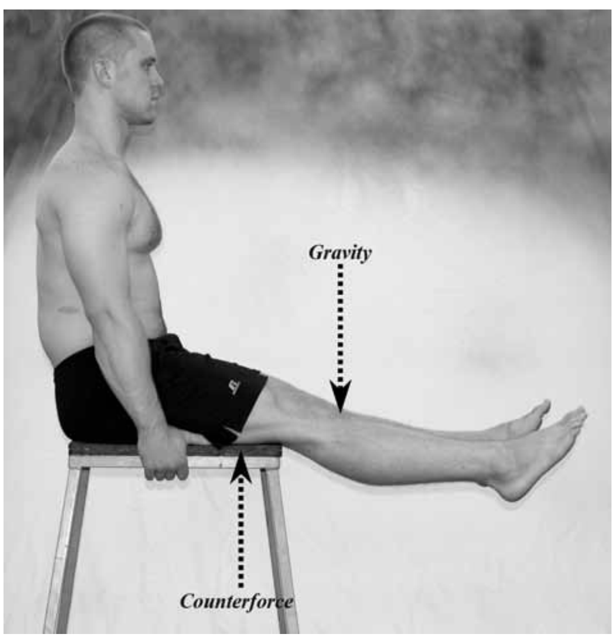
Muscular contraction alone, muscular contraction in concert with or against gravity, or muscular contraction acting together or in opposition to gravity and other bodies can produce any of the forces described here. And that is an important concept to understand. The body can experience these forces from external application, and it can also produce the forces described through contraction.

Using the forces

But let's turn to another issue related to force production: the balancing of forces across a joint. In most instances during exercise we want to create, through muscular contraction, an unbalanced force across a joint or joints in order to create movement. If I am down in a squatting position and I want to stand up, I have to generate a force with my hip and knee extensors that is greater than the effects of gravity on my body mass. If a greater force does not work in the direction opposing gravity, either because of weakness or because of an additional load on my shoulders, I cannot stand up. That is usually a bad thing.

> Any movement of the human body, by definition, must be the result of an unbalanced force, and the magnitude of force produced by the agonist is irrelevant to a predetermined ratio.

But when we consider joint integrity during movement, it is often proposed that we need to balance forces across the joint in order to stabilize it. This point is interesting: we do need to counter any force that actively attempts to engage ligaments at their limits (muscles and tendons try to keep joints pulled together while ligaments act only



Courtesy of Dr. Lon Kilgore

FIGURE 4:
Shear occurs when two segments of the body are pushed in opposite directions. In the example here, the table provides an upward force on the thigh, and gravity provides a downward force on the unsupported lower leg. This places a shear force on the knee. If the complete musculature surrounding the knee is well developed this is not a problem. If an injury exists, or in conditions of extremely low fitness, shearing force can produce movement (shear), which may be a problem.

to prevent them from separating). For example, having the hamstrings and quadriceps co-contracting effectively during squatting prevents forward or backward movement of the knee joint (shear between the femur and tibia). This is a good thing. But how do we manage to produce an unbalanced force driving movement and then balance force across a joint?

That brings us to the final order of business, a consideration of agonist (primary mover) and antagonist (resists the action of the primary mover) muscles and the mythical optimal strength ratios. It is common to see suggestions that there is clinical and exercise-training relevance produced by dividing things like hamstring strength by quadriceps strength to obtain an indication of muscular balance. It is frequently suggested that the agonist-antagonist ratio should approach 1:1 in rehabilitation and exercise settings. The International Fitness Professionals Association provides the following strength (force-generating) standards to its members:

Muscle groups	Balance ratio
Ankle inverters and everters	1:1
Ankle plantar flexors and dorsiflexors	3:1
Elbow flexors and extensors	1:1
Hip flexors and extensors	1:1
Knee flexors and extensors	2:3
Shoulder internal and external rotators	3:2
Shoulder flexors and extensors	2:3
Trunk flexors and extensors	1:1

A problem with this concept is that it is not reflective of real-world movement. The leg-extension and leg-curl exercises, involving only the knee, are the usual tests of lower-body muscular balance (because every fitness club and clinic has these machines). These two movements do not occur during normal human ambulation, sport or exercise movement without being accompanied by other joint movements. The same can be said of the other muscle groups listed and their methods of assessment.

More importantly, a second problem is that these ratios are frequently interpreted to imply that the opposing groups are active during activity at the ratio listed. This leads to a misunderstanding of the fact that any movement of the human body, by definition, must be the result of an unbalanced force, and the magnitude of force produced by the agonist is irrelevant to a predetermined ratio.A balanced force across a joint is not the same as "strength balance" between agonists and antagonists. A precisely balanced force across a single joint would result in an isometric muscle action and produce no movement. Antagonist muscles are not recruited extensively or are inhibited in force production in order to allow the agonist to drive movement. In fact, one of the first basic physiological adaptations the body makes in the first few months of training is learning how to turn off antagonist muscles more completely in order to maximize the efficiency of the agonist muscles in executing a movement. Less resistance from the antagonist means more available force from the agonist.

A one-size-fits-all statement about optimal strength balance is not possible, and if someone does per chance hear or read about one, know that it cannot provide us with any practical advantage in coaching in the gym.

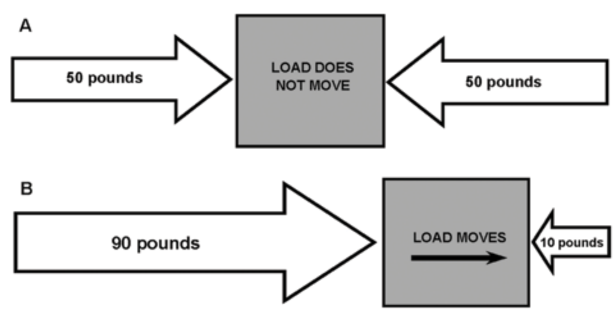


FIGURE 5:
In the balanced-force case here (a), equivalent and opposing forces cannot induce movement. Only with an unbalanced-force scenario (b), where one directional force has a magnitude greater than the opposing directional force, can a load be moved. The greater the difference in magnitude between the opposing forces, the more impulse available to move the load quickly.

This renders the 1:1 (or 2:3 or 3:1, etc.) concept of strength balance irrelevant during movement. If it takes 25 kilograms of posterior force to maintain knee-structure stability during movement, does it make any difference if the muscles providing that force can, at maximum effort, produce 50 kilograms of force or 500? Not really. Obviously, a minimum level of force is required to maintain structural integrity of joints, and stronger is always better, but the ratio of agonist-antagonist force production during movement is a function of physical task requirements and individual anatomy.

This does not mean that an antagonist muscle may not be active during agonist contraction. Think about the hamstrings (biceps femoris, semitendinosis and semimembranosis) when one stands up out of the bottom of a squat. The hamstrings are normally thought of as antagonists to the quadriceps (vastus medialis, vastus lateralis, vastus internus and rectus femoris). They are quite active in this movement but not as antagonists to the knee extensors: they are themselves agonists in hip extension. That is their job. That is the job of all muscles: to produce, not resist, large-scale joint movement. In our squat example, the traditionally held antagonist muscles simply, as part of their roles as prime movers, generate the necessary joint stabilizing counter-forces. This is an involuntary by-product of basic anatomy, physiology and physics.

Do not get me wrong: antagonists are important as they assist in deceleration, stabilization and fine motor control, but the notion that we can magically determine how strong the multitude of agonist and antagonist muscles—the ones active in simple exercise—need to be is not practical. Measurable estimations of the relative contributions of individual or groups of agonists and antagonists during complex movements are not well known, especially in fit populations, so how can we construct a hierarchy of concepts and terminology based upon something that is so poorly understood?

A one-size-fits-all statement about optimal strength balance is not possible, and if someone does per chance hear or read about one, know that it cannot provide us with any practical advantage in coaching in the gym. It is our charge to develop our trainees to be fully functional, able to both tolerate and produce a complete spectrum of real forces. We need not minimize the forces presented during training or tune force-generation capacity to a hypothetical ratio. The best advice is to strengthen all relevant axes of movement around a joint.

For example, if you bench press, then you need to press, dip, chin and do deadlifts or rows to "balance" the strength of the muscles around the shoulder joint. If a complex movement develops force-generation capacity in multiple axes around a joint, then forgo isolation exercises, as strength balance will be naturally obtained during the execution of the compound exercise (think of how this happens in the squat).

Where force production is concerned, we need to focus on programming exercises to improve force production, force tolerance, and absolutely of most import, functional fitness enhancement for the real world.

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About the Author

Lon Kilgore is a professor at Midwestern State University, where he teaches applied physiology and anatomy. He has also held faculty appointments at Kansas State University and Warnborough University (IE). He graduated from Lincoln University with a Bachelor of Science in biology and earned a PhD in anatomy and physiology from Kansas State University. He has competed in weightlifting to the national level since 1972 and coached his first athletes to national championship event medals in 1974. He has worked in the trenches, as a coach or scientific consultant, with athletes from rank novices to professionals and the Olympic elite, and as a collegiate strength coach.

He has been a certifying instructor for U.S.A. Weightlifting for more than a decade and a frequent lecturer at events at the U.S. Olympic Training Center. His illustration and authorship efforts include books, magazine columns and research journal publications.