The Study of Human Movement by the Application of Biomechanical Musculoskeletal Leverage Physics: Understanding the Effective Lever Arm.

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Biomechanical study utilizing musculo-skeletal leverage physics to produce reliable and useful results concerning the reconstruction of the musculo-skeletal system's performance in physical events. James G. Hay in his book, The Biomechanics of Sports Techniques, defines biomechanics as a study in musculo-skeletal leverage. His abridged definition includes, "The study of forces acting upon the musculo-skeletal system, produced by the musculo-skeletal system and then impacting within the musculo-skeletal system". HAY, JAMES G., (1993) *The Biomechanics of Sports Techiques* . 4th ed. New Jersey:Prentice-Hall Inc. A Simon & Schuster Company Englewood Cliffs.

From simply lifting a weight, to carrying a 120 lb. sack of grain on your back, biomechanical leverage physics reveals the amount of muscle effort required at the joint, which joint tissue is used, and the effort necessary to support the combined force of the weight and muscle. The 120 lb. study of the spine was first done by Giovanni Alfonso Borelli in 1660. Borelli demonstrated there were over 25,000 lbs. of force roduced and stabilized by the muscles and joints of the spine in this event. BORELLI, A.G., (1989) *On the Movement of Animals,* Berlin NY:Springer-Verlag.   POPE, M.H., (2005) Alfonso Borelli The Father of Biomechanics. *SPINE*, 30(20) 2350-2355.

This mathematically based technology can potentially produce a broad spectrum of information for various specialties. In sports, it can be used as a predictor of athletic success. In forensic pathology, it can develop a roadmap of which tissues would be predictably injured and to what degree. In physical anthropology, its application would lead investigators to know where to look for musculoskeletal stress markers when trying to determine evidence of human activity during physical tasks.
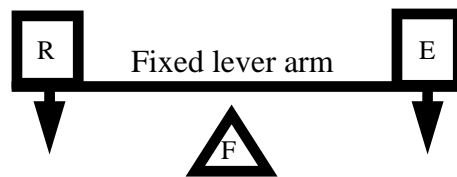
At the heart of studying the musculoskeletal leverage system is understanding the effective lever arm. The effective lever arm was first discovered and published by

Benedetti in 1599 (De Mechanicis, Benedetti, G.B., Venetiis (Venice): Apud Baretium Baretium, & Socios, 1599. For the first time in history, this finding, enabled man to truly know how forces like actual muscle effort impacted the lever system.

To fully appreciate the importance of Benedetti's discovery, one must examine the musculoskeletal system functioning as a lever system at work.

A simple lever system consists two opposing forces acting on a solid bar that would cause the solid bar to move about a fulcrum. "Solid" in this instance in the physics of leverage is known as fixed. The fixed (solid) portions of the lever system are known as the "fixed lever arms" of the lever system.
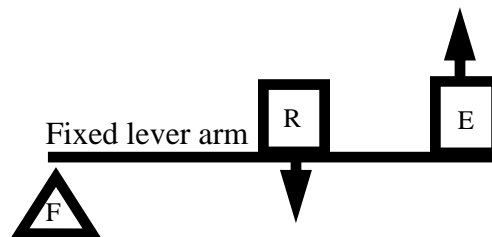
Figure 1

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R        Fixed lever arm        E
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Force R pulls down on the bar (fixed lever arm). This would cause the entire bar to rotate at F (the fulcrum) downward in the direction of the force.
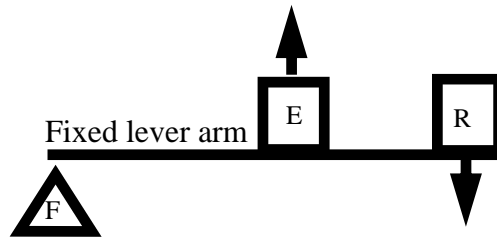
Force E opposes Force R and would cause the bar (fixed lever arm) to move downward on this side at the fulcrum.

Figure 2

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Fixed lever arm    R        E
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Force R would pull the bar (fixed lever arm) down causing it to rotate downward at the fulcrum (F). Force E would oppose Force R and would cause the bar (fixed lever arm) to move upward and rotate at the fulcrum upward.

Figure 3

Fixed lever arm E   R   F

Force R would pull the bar (fixed lever arm) down causing it to rotate downward at the fulcrum (F). Force E would oppose Force R and would cause the bar (fixed lever arm) to move upward and rotate at the fulcrum upward.

In the human body, bones function as fixed lever arms. The joint or articulation acts as the fulcrum. Two opposing forces are created by weights that move the bones around their mutual joint. The weight can be supplied by an external mass (Force R), as in the weight of a barbell, that would cause the fixed lever arm to rotate about the joint. The weight (Force R) could also be supplied by an internal mass, as in the weight of an arm acting on the fixed lever arm (bone), causing it to rotate about the joint.   Force E is the amount of weight a muscle produces on a fixed lever arm (bone) that would cause a rotation opposite to force R at the joint.

Of these two opposing forces acting on the fixed lever system, one force is termed the force of resistance (Force R) and the other force is termed the force of effort (Force E). In the applied technology of leverage relative to musculo-skeletal system, Force R is typically identified as that force acting on the lever that does not possess variability. Force E that opposes Force R possesses variability, meaning its magnitude force can be manipulated by some intelligent means.

In the study of musculoskeletal leverage the external weight (barbell) or internal weight (body mass) would be termed the force of resistance (Force R). The force that the muscle can produce, because it can be intelligently and discriminately be increased or decreased

and therefore possesses intelligent variability at the discretion of an intelligent source, is termed the force of effort (Force E).

The fixed lever arms rotate around the fulcrum in the direction of the greater force.

If the two forces are equal in their magnitude and there is no net movement by the fixed lever arms at the fulcrum, then the lever system is said to be stable or in equilibrium. Equilibrium means that the two opposing forces are equal and therefore no rotation occurs.
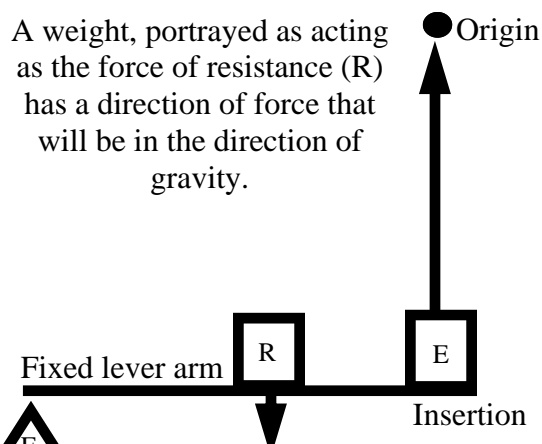
When biomechanically applying the principles of leverage physics to study of musculo-skeletal movement, there are important factors concerning the force of resistance and the force of effort. One of these factors concerns the typically consistent direction of the force of resistance and the typically changing direction of the force of effort.

During human movement when the force of resistance is created from the pull of gravity, as the force of resistance moves about the fulcrum it will continually possess a direction of force aligned with the pull of gravity. This would typically be the case when examining for instance the weight of the body or lifting a weight.
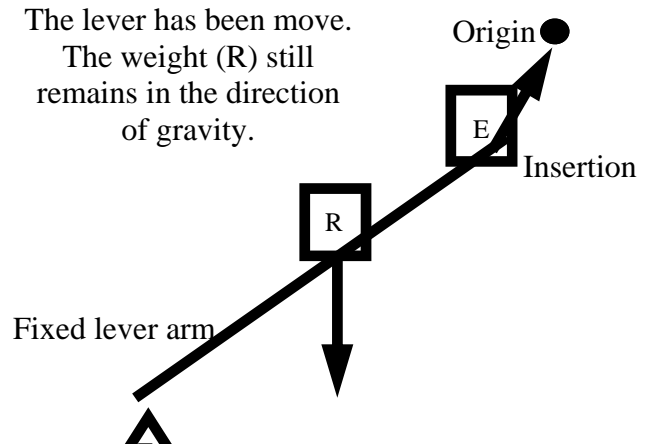
When a muscle producing the force of effort moves about the fulcrum, it will possess a linear direction of force that will follow from the muscle's insertion on the fixed lever arm back to the muscle's origin. Since the insertion and origin of a muscle is fixed, as the levers (bones) move about the fulcrum (joint), the direction of force will change throughout the movement.

Figure 4

A weight, portrayed as acting as the force of resistance (R) has a direction of force that will be in the direction of gravity.

●Origin

The lever has been move. The weight (R) still remains in the direction of gravity.

Origin●

E

Insertion

R

Fixed lever arm
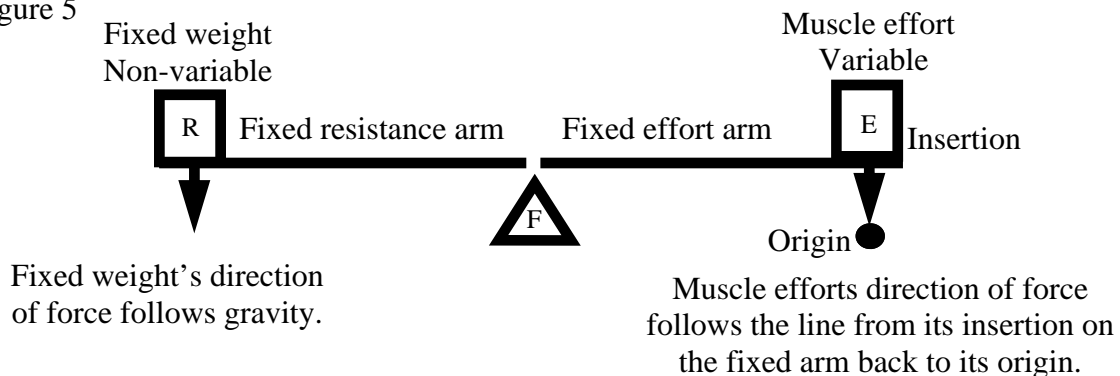
Fixed lever arm

R

E

Insertion

The weight of each of the two forces is not the only factor that determines the ultimate magnitude in the lever system. The other factor is their relative distance from the point of application back to the fulcrum.

The distance from the point of application of Force E and Force R on the fixed lever back to the fulcrum, historically but erroneusly has been taught as having significance relative to how a lever actually function in the production of force for leverage.

For instance traditional physics teaches there are 3 classes of a lever system and the identification of these classes is based on the identification of the points at which the force of effort and force of resistance are applied to a fixed lever relative to the position of the fulcrum. It is taught that the identification of these classes is important because they possess significance realtive to the production of force. The teaching of functional significance relative to lever classes is erroneus and we will demonstrate this later in this class with physics proofs.

The distance from the fulcrum to the point on a fixed lever arm that the effort attaches is known fixed effort arm length. The distance from the fulcrum to the point on a fixed lever arm that the resistance attaches is known as the fixed resistance arm length.

Figure 5

Fixed weight
Non-variable

Muscle effort
Variable

R   Fixed resistance arm   Fixed effort arm   E   Insertion

F

Origin

Fixed weight's direction
of force follows gravity.

Muscle efforts direction of force
follows the line from its insertion on
the fixed arm back to its origin.

From Archimedes's time to the present, academics continues to teach relative to the structural identification of lever systems that effective point of force application (Force R and Force E) is the point at which the force of both the resistance and the effort attach on the fixed lever arms. . It is taught that the identification of these classes is important because they possess significance realtive to the production of force. The teaching of functional significance relative to the 3 lever classes is erroneus and we will demonstrate this later in this class with physics proofs. The distance from the fulcrum to the point on a fixed lever arm where the force of resistance or force of effort attaches possesses no significance to how a lever system produces force. We are going to be learning that it is the direction of which the force of resistance or effort is applied that is important and that this direction forms the basis of the the "effective lever arm".

Around 200 BC, Archimedes determined an equation to establish equilibrium within a lever system using the variables described above. His formula is known as the Equilibrium of Torque.

Defined within the Equilibrium of Torque, when the effective force of resistance and the effective force of effort acting on the fixed lever arms are equal there is no movement or torque, causing the fixed arms to rotate at the fulcrum.

The formula for equilibrium of torque is:

Weight of the resistance (Force R) x the length of the resistance arm =
Weight of the effort (Force E) x the length of the effort arm.

This equation is used to this day in modern lever analysis when determining lever Equilibrium of Torque.

Notice! Notice! Important!   We have reached the significant teaching point about effective lever arms.

The formula for equilibrium of torque from Archimedes time read:

Weight of the resistance (Force R) x the length of the "FIXED" resistance arm =
Weight of the effort (Force E) x the length of the "FIXED" effort arm.

The formula for equilibrium of torque in modern day physics is:

Weight of the resistance (Force R) x the length of the "EFFECTIVE" resistance arm =
Weight of the effort (Force E) x the length of the "EFFECTIVE" effort arm.

An understanding of what the effective arm is and how it effects force production in a lever system is of the greatest importance and needs to be taught to correct mass intellectual thinking relative to leverage.   What significant result you are going to find is how current physics still teaches the 3 classes of levers based on the structural but non functional "FIXED" lever and how lever identification should be based on the functional "EFFECTIVE" lever. So where did the effective lever arm come from?

In 1599 however Italian mathemetician Giovanni Alfonso Benedetti published work wherein he proved that the distance at which the force of effort or resistance was applied to the fixed lever arm was not the distance that determined the total magnitude of the respective forces impacting on the lever system. He more precisely defined the resistance arm as the distance perpendicular to the direction of the resistance force back to the fulcrum. He similarly defined the effort arm as the distance perpendicular to the direction of effort force back to the fulcrum. These important observations by Benedetti have either been overlooked or misunderstood through the ages. What Benedetti discovered and defined is now known as the "EFFECTIVE" lever arms.

Benedetti's effective effort arm or effective resistance arm now occupies the same space as the fixed effort arm or fixed resistance arm did respectively within the Equilibrium of Torque equation derived by Archimedes:

The weight of the resistance (Force R) x The length of the EFFECTIVE resistance arm =
The weight of the effort (Force E) x The length of the EFFECTIVE effort arm.

Though the lengths of each arm occupy the same place in the above equation, they do not always occupy the same space as the fixed resistance arm and fixed effort arm within the lever system. Benedetti demonstrated that as a lever moves through a range of motion

the fixed arms and effective arms do not occupy the same space.   In other words the length of the fixed lever arm distances will not change throughout a movement but the length of the effective lever arm will.

Figure 6 shows a classic 1st class lever system with the fixed resistance arm and the fixed effort arm superimposed with the effective resistance arm and the effective effort arm.
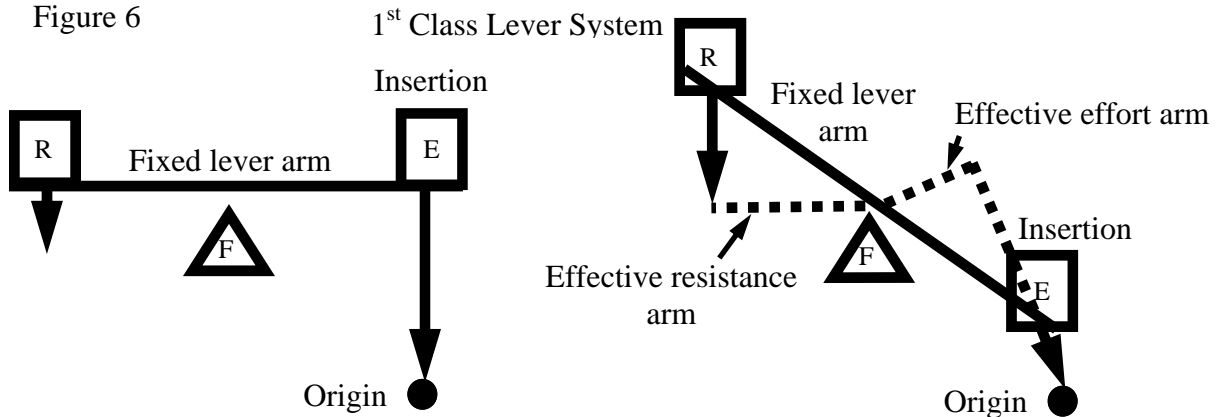
Figure 6   1st Class Lever System

Insertion

R   Fixed lever arm   E

F

R

Fixed lever arm

Effective effort arm

Insertion

F

E

Effective resistance arm

Origin   Origin

Figure 7   2nd Class Lever System

The muscle effort's direction of force follows the line of pull of the muscle from it's insertion back to it's origin. The origin and insertion are fixed points on the fixed arms.

Origin

Origin

E

Insertion

Fixed lever arm   R   E

R

Fixed lever arm

Insertion

F

Effective resistance arm (1.21")   Effective effort arm (2.16")
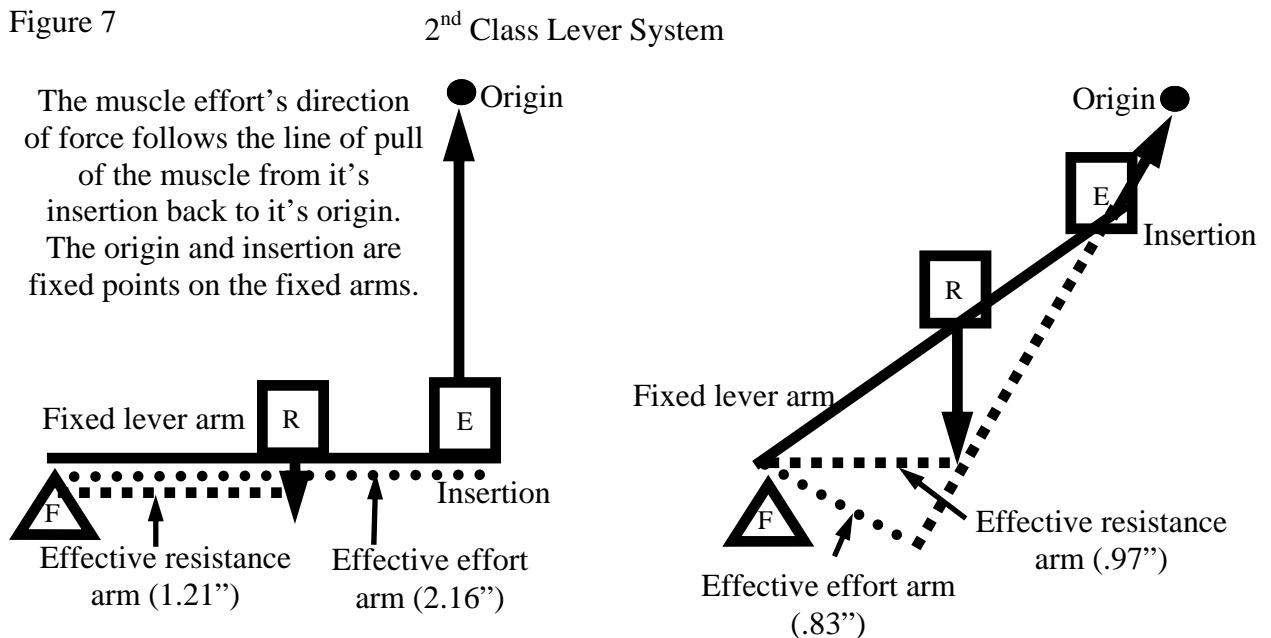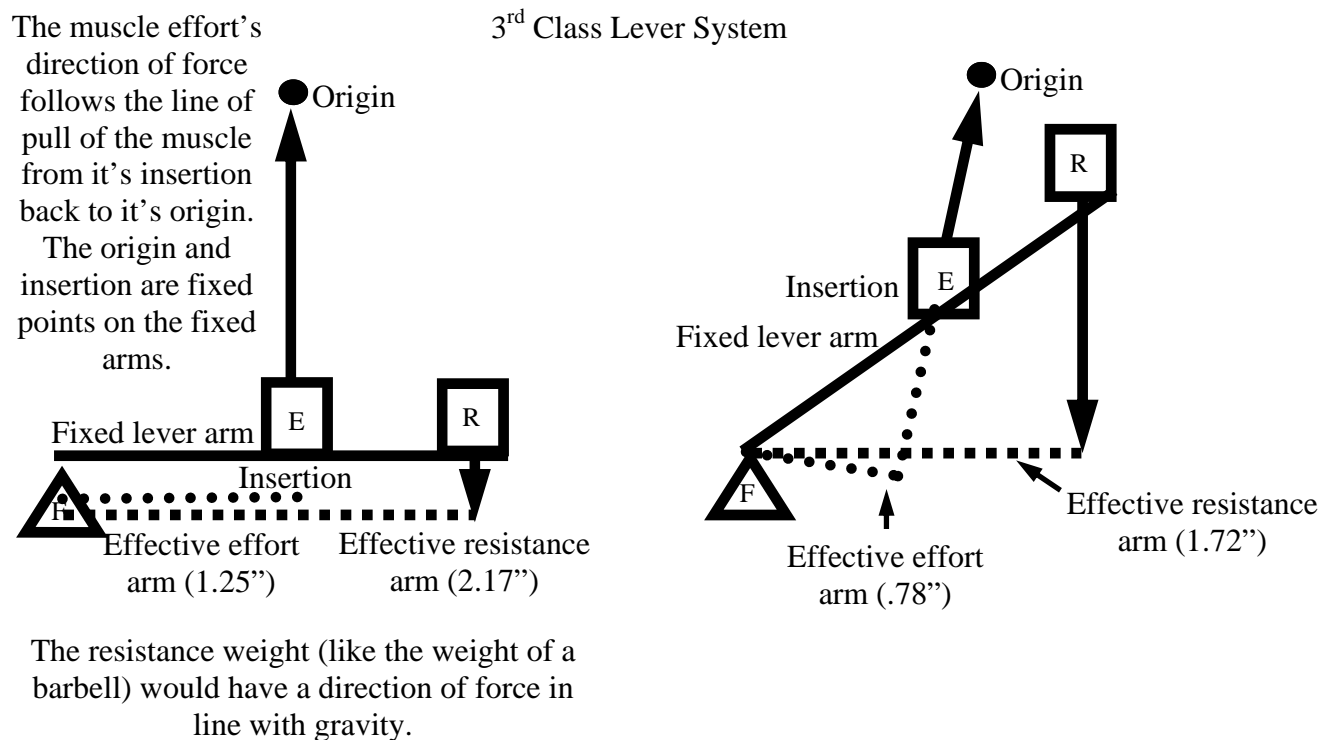
F

Effective effort arm (.83")

Effective resistance arm (.97")

The resistance weight (like the weight of a wheelbarrow) would have a direction of force in line with gravity.

Using the classic 2nd class lever system in figure 7, the effective effort arm (2.16") is longer that the effective resistance arm (1.21"). When moving the lever through a range of motion, the effective effort arm actually became shorter than the effective resistance arm. The length of the effective resistance arm is .97" long whereas the length of the effective effort arm is .83" long. Since the effective effort arm is shorter than the effective resistance arm, at this point in its movement, this 2nd class lever possesses poor mechanical advantage. Poor mechanical advantage means it takes more force of muscle effort than force of resistance to maintain the lever system in equilibrium.

Figure 8

The muscle effort's direction of force follows the line of pull of the muscle from it's insertion back to it's origin. The origin and insertion are fixed points on the fixed arms.

3rd Class Lever System

Fixed lever arm

Origin

Insertion

Effective effort arm (1.25")   Effective resistance arm (2.17")

The resistance weight (like the weight of a barbell) would have a direction of force in line with gravity.

Origin

R

Insertion   E

Fixed lever arm

Effective resistance arm (1.72")

Effective effort arm (.78")

In the 3rd class lever system depicted in figure 8, the effective effort arm (1.25") is shorter than the effective resistance arm (2.17"). After moving the lever through a range of motion, the effective effort arm remained shorter (.78") than the effective resistance arm (1.72").

DISCUSSION

When examining the classical (current) teaching of levers and their inherent mechanical leverage properties one can see that as the lever system translates through a range of motion, the fixed lever arms and effective lever arms differentiate and demonstrate their own very independent structural and functional impacts on the lever system.

Benedetti's observations revealed that when determining mechanical advantage, especially in biomechanical leverage studies involving fixed muscular attachments, the current teaching of lever systems employs erroneous tools. The key difference is that the forces of resistance and effort effectively work on the lever system relative to the distance perpendicular to the direction of their application.

In the study of leverage, understanding how the forces of effort and resistance effectively work through a distance on the lever system is important because it demonstrates the true mechanical advantage of the lever system. When it takes less force of effort to than the force of resistance to put a lever system in equilibrium, the system is said to have good mechanical advantage. When it takes more force of effort than the force of resistance to put a lever system in equilibrium, the system it is said to have poor mechanical advantage.

Currently, 1st class levers can have either good or poor mechanical advantage depending on the distance at which the force of resistance or force of effort is applied to the fixed lever arms as measured from their points of attachment or influence.

It is commonly thought that 2nd class levers possess good mechanical advantage because the distance at which the force of effort affects the fixed lever arms is longer than the distance at which the force of resistance affects the lever arm. However, this paper outlines the inherent inconsistency of this.

Finally, 3rd class levers are taught to possess poor mechanical advantage because the distance at which the force of effort affects the fixed lever arm is longer then the distance at which force of resistance affects the fixed lever arm.

Currently in academics, the impact of the resistance and the effort is calculated as being the physical distance from each respective point back to the fulcrum. After incorporating Benedetti's concepts, it is necessary to study the effective impact on the lever system by looking at the distance perpendicular to the force of resistance and the force of effort relative to the fulcrum.

From MSN Encarta encyclopedia defining Lever:
http://encarta.msn.com/encnet/refpages/RefArticle.aspx?refid=761567646

> "The mechanical advantage (MA) of a lever tells how much the lever magnifies effort. In practical terms, the MA is the distance of the force of effort to the fulcrum divided by the distance of the load (force of resistance) to the fulcrum. Depending on the class of lever and the location of the fulcrum, the MA may be less than or greater than 1."

> "The 2nd class has the fulcrum at one end, the force at the other end, and the load in the middle. A common example is the wheelbarrow, where the wheel is the fulcrum, the load rests within the box, and the force is the lift supplied by the user. A CLASS 2 LEVER "ALWAYS" HAS MECHANICAL ADVANTAGE GREATER THAN 1. This because the distance of the force of effort as it is applied to the lever arm is "ALWAYS" greater then distance at which the force of resistance is effectively applied back to the fulcrum."

The above excerpts from Encarta illustrate how current lever teaching applies the distance of either effort or resistance on their fixed points on the fixed arms and not the effort or resistance effective arms. As previously illustrated in our example of the 2nd class lever moved through a range of motion, a 2nd class lever does not "always" have a mechanical advantage greater than 1.

CONCLUSION

Whenever studying levers or biomechanics of muscular skeletal leverage, the distinction must be made between the distance of the fixed versus effective lever arms. The fixed lever arms are the distance from point of application of either resistance or effort force back to the fulcrum. The effective lever arms are the distance perpendicular to the line of force back to the fulcrum.

The distinction must be made in academics that when determining the mechanical advantage of a lever system, it is the effective lever arm distances that must be discovered and used in the equilibrium of torque formulae and not the fixed distances that contemporary academics teaches.

The material presented in this paper may well serve future clinical investigation into the mechanical forces of traditional weight training exercises and the impact of those forces on the biomechanical integrity of joints. Dissemination of the information contained in this paper is recommended for the study of musculoskeletal injury mechanisms and joint rehabilitation.