

Biomechanics of Resistance Exercise

Cody Sipe, PhD

Why study biomechanics?

Safety

- Should a client with B/L knee arthritis perform a deep squat?
- Why does an individual experience shoulder pain when lifting their arms and how do I “fix” it?
- How does a person lift heavy weight from the floor without injuring their back?

Effectiveness

- How does arm position affect the work of rectus abdominis during a crunch?
- Why does a quick counter-movement create greater height on a vertical jump test?
- How can I train the core musculature to maximize spine sparing and lifting performance?

Efficiency

- How do we train someone for maximum results with minimal time and effort?
- How can an individual with physical limitations perform functional tasks without expending unnecessary energy?

The science of biomechanics enables us to answer these questions accurately.

Important Terminology

Lever – rigid bar that has an axis of rotation (A) and a point at which force is applied (F), and a resistance which must be balanced or overcome (R)

Fulcrum – axis of rotation

Effort Force (EF) – force required to overcome a resistance or load in order to resist or produce motion usually created by muscles

Resistance Force (R or RF) – load being moved, force applied externally (not to imply it is always external)

Important Terminology

Lever Arm (LA) – distance from the axis of rotation to the point at which force is applied to the lever.

Effort Arm (EA) or Force Arm (FA) – distance from EF to fulcrum.

Resistance arm (RA) – distance from RF to fulcrum

Moment – a rotary force on a lever (which produces torque)

Types of Levers

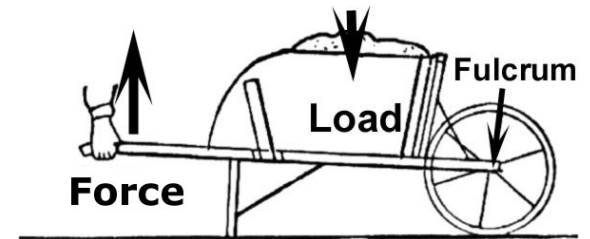
First Class

- Axis/fulcrum in middle
- Seesaw, Cranium on spine
- Mechanical Advantage (MAd) can vary widely



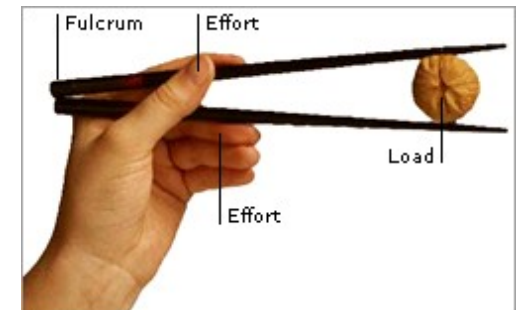
Second Class

- RF between axis/fulcrum and EF
- Wheelbarrow, Gastroc/ankle in walking
- Most efficient (MAd > 1.0)



Third Class

- EF between axis/fulcrum and RF
- Least efficient (MAd < 1.0)
- Most common in the human body, Elbow flexion



Forces

Force: Mechanical disturbance or load; ***push or pull*** of one object on another; something that causes motion, a change in motion or a change in the shape of a system (also called load)

$F=MA$ (mass x acceleration)

mass = kg; acceleration = m/s^2

1 Newton = $1 \text{ kgm}/s^2$

Description of Forces

1. Active or passive
2. Internal or external
 - Internal: muscles, ligaments, joint capsule
 - External: gravity, physical contact, load, ground reaction
3. Types: Tension, compression, bending, shear, torsion, combined
4. Translational or rotational
 - Translation: all points move parallel
 - Rotation: all points move in the same angular direction
5. Frictional

Line of Gravity: Vector

Most common and consistent external force vector encountered by the human body

- Magnitude: Weight ($\text{mass} \times 9.8\text{m/s}^2$)
- Spatial Orientation: Vertical
- Direction: Down (inferior, caudal)
- Point of Application: Center of Mass

Center of Mass:

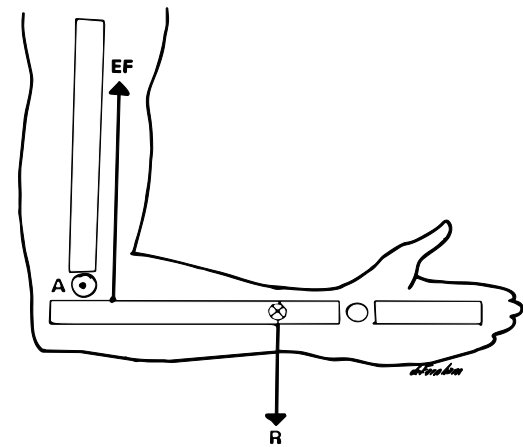
- location of the average of all mass in the human body
- typically in the center of the body just above the navel
- can be shifted by limb position, obesity/pregnancy, posture, etc.
- ALSO the location of the average of all mass of a limb segment

Why have 3rd class levers if they are inefficient? The benefits are Speed and Distance

Trade-off between force and speed,
force and distance

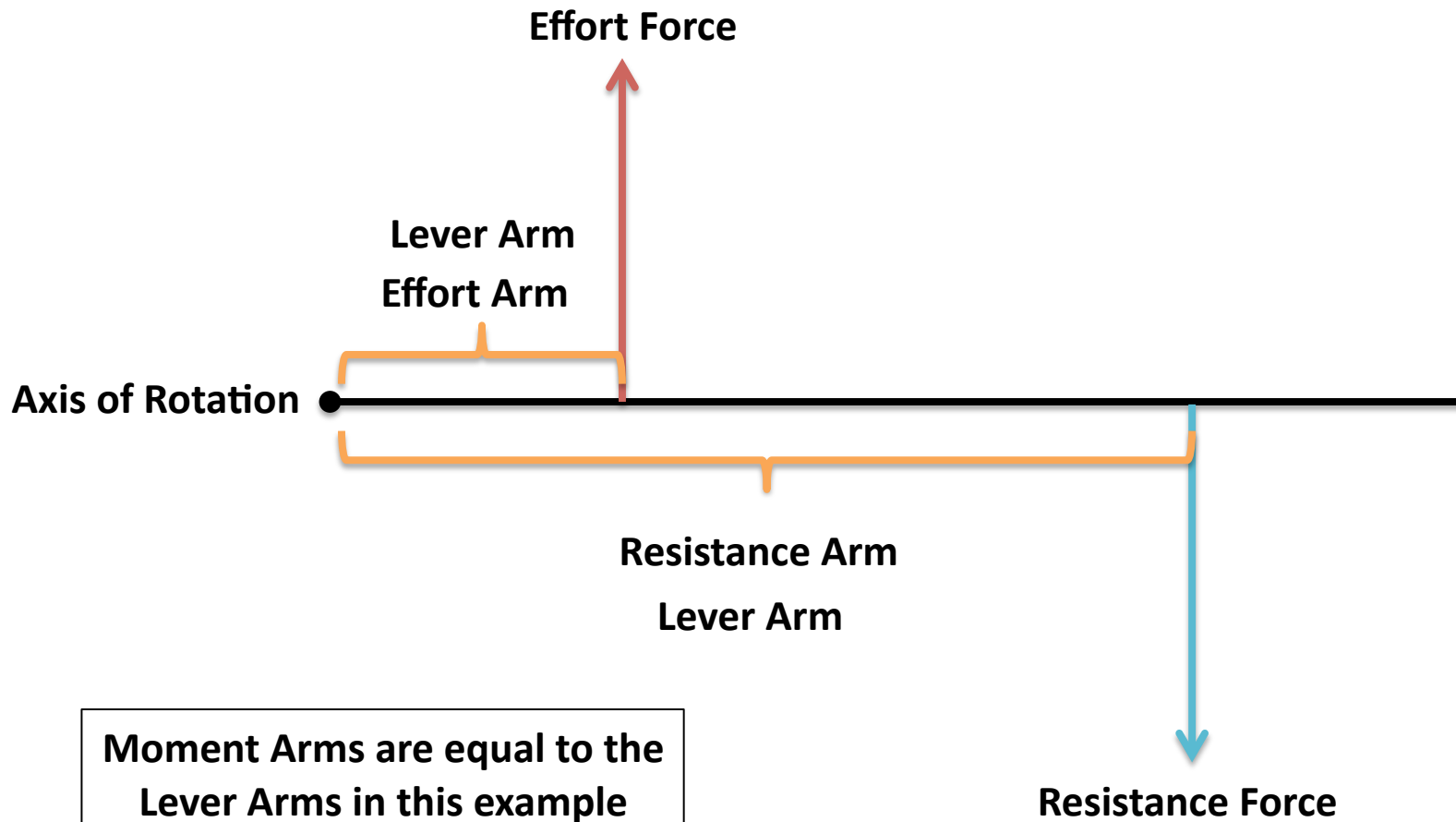
More force is required **but**...

- Muscle contracts at a much smaller distance than the lever arm moves;
- Lever arm moves much faster than the rate of muscle contraction



EA = 5cm
RA = 35cm
EA = 11.6cm/sec
RA = 82.5cm/sec

Lever Systems

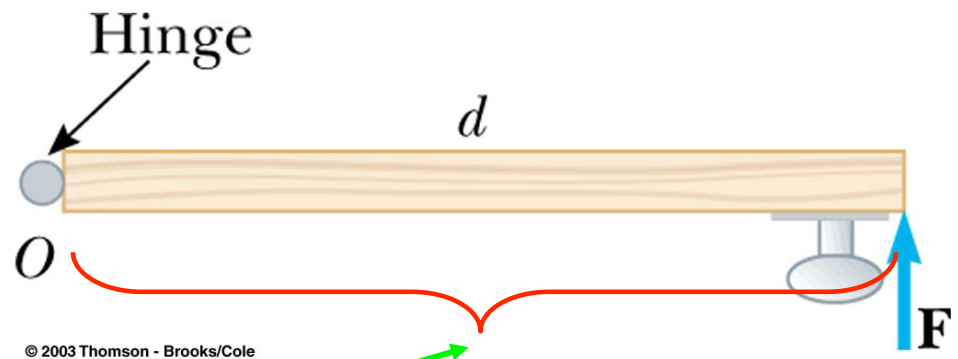


Torque

Torque, τ , is the tendency of a force to rotate an object about some axis

Door example:

$$\tau = Fd$$

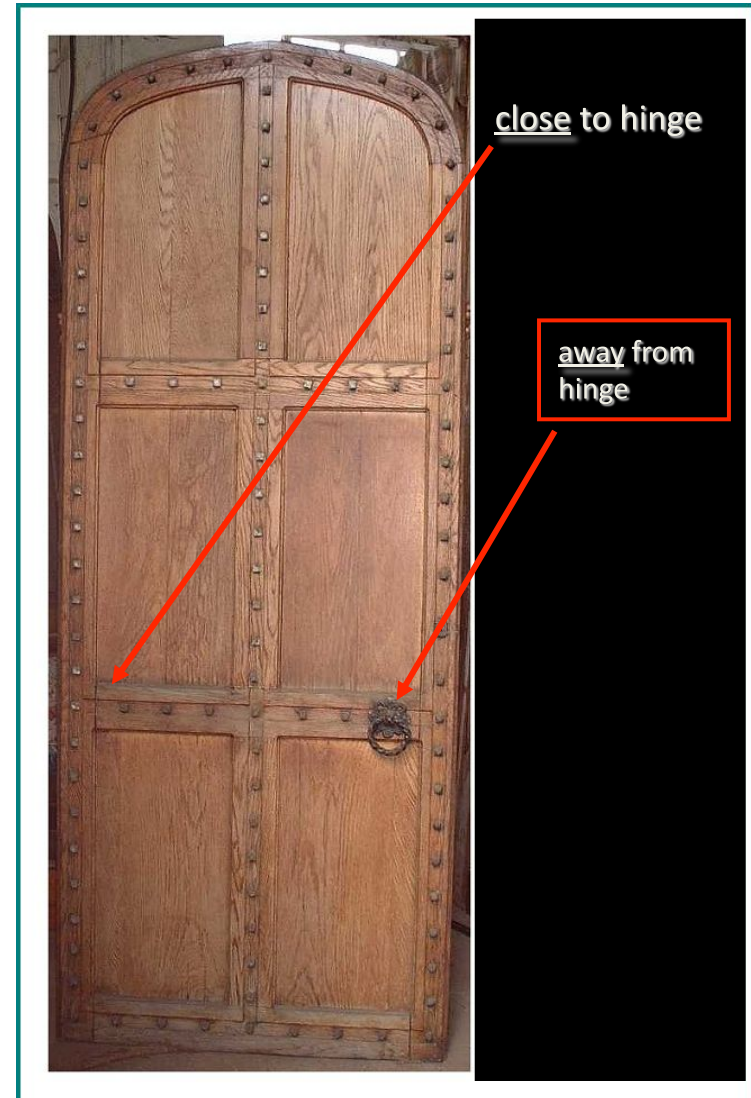


- τ is the torque
- d is the *lever arm* (or *moment arm*)
- F is the force

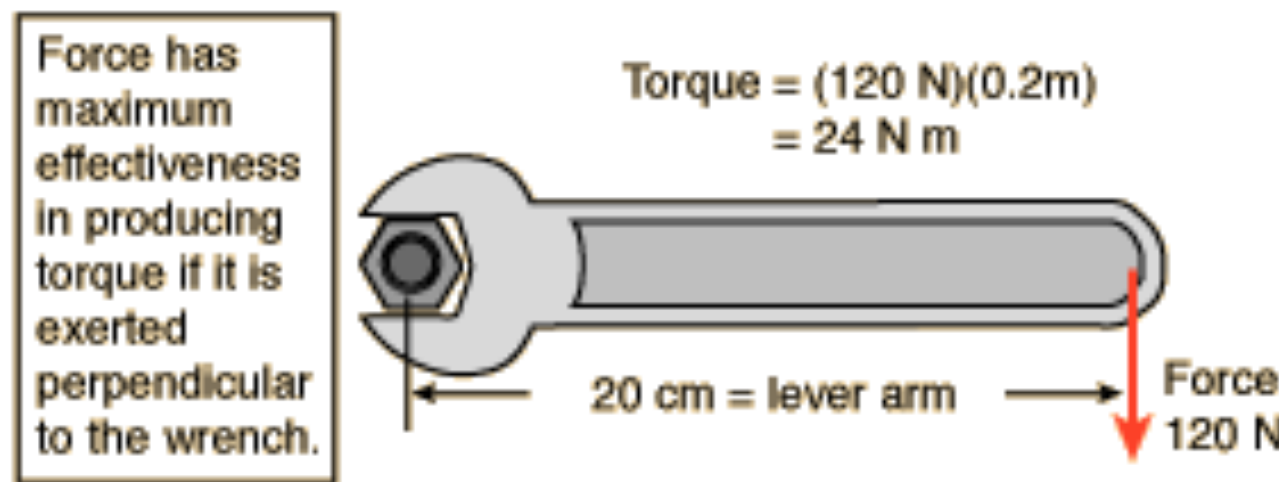
Torque

Consider force required to open door. Is it easier to open the door by pushing/pulling away from hinge or close to hinge?

Further from hinge, of course!



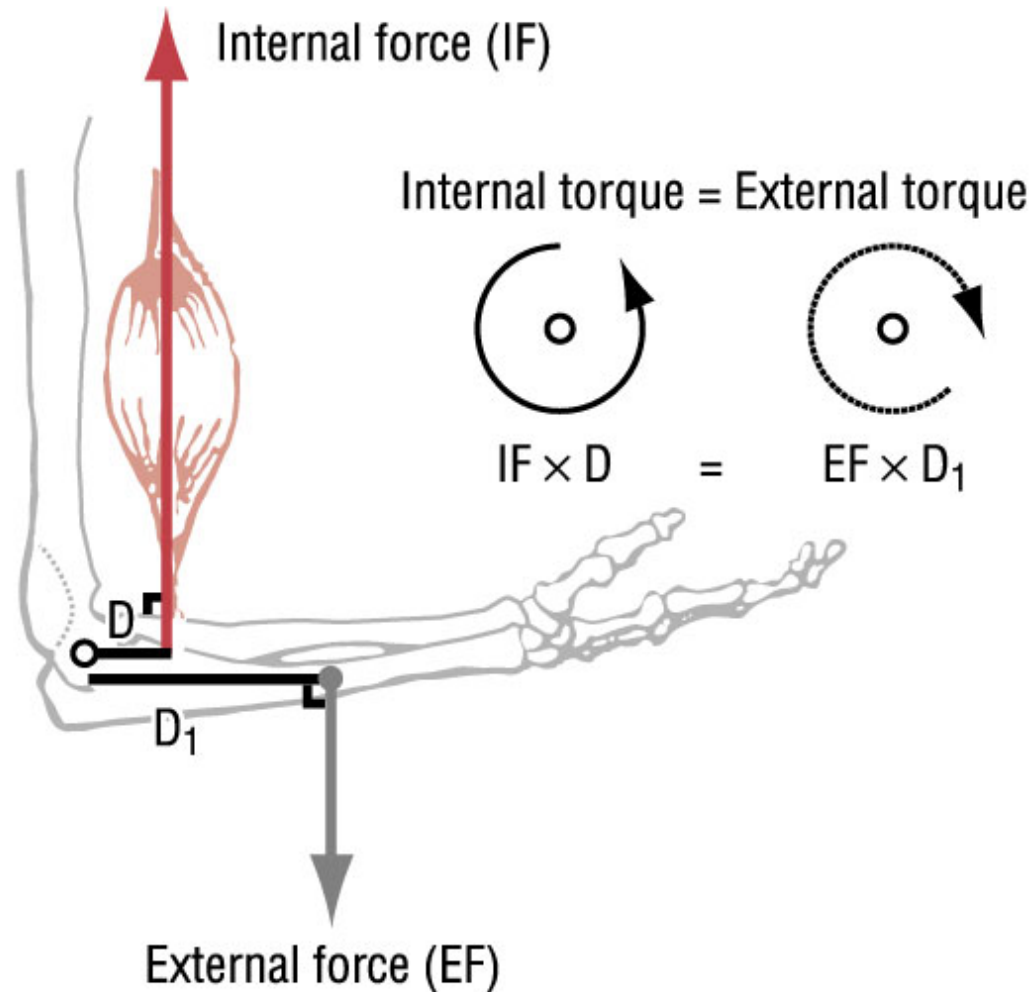
Torque – the tendency of a force to rotate a lever about a point ($F \times D$)



Stumper

A strongman is trying to change a tire. He can apply 1,000N of force to his 50cm long tire iron but the lug nut won't budge. A 7 year old boy offers to help but he can only generate 100N of force. The strongman laughs and goes to get a protein shake. When he returns the lug nut is off and the young boy isn't even sweaty. He promises he did not use any power tools or get help from anyone else. How might he have done it?

Torque (Nm)



Mechanical advantage (MAd)
– refers to the efficiency of
the lever

**MAd = Effort Arm/Resistance
Arm**

**When MAd >1, then Effort
Force can be smaller than
Resistance Force.**

**Simply, the greater the MAd,
the less Effort Force required
to move a given Resistance
Force.**

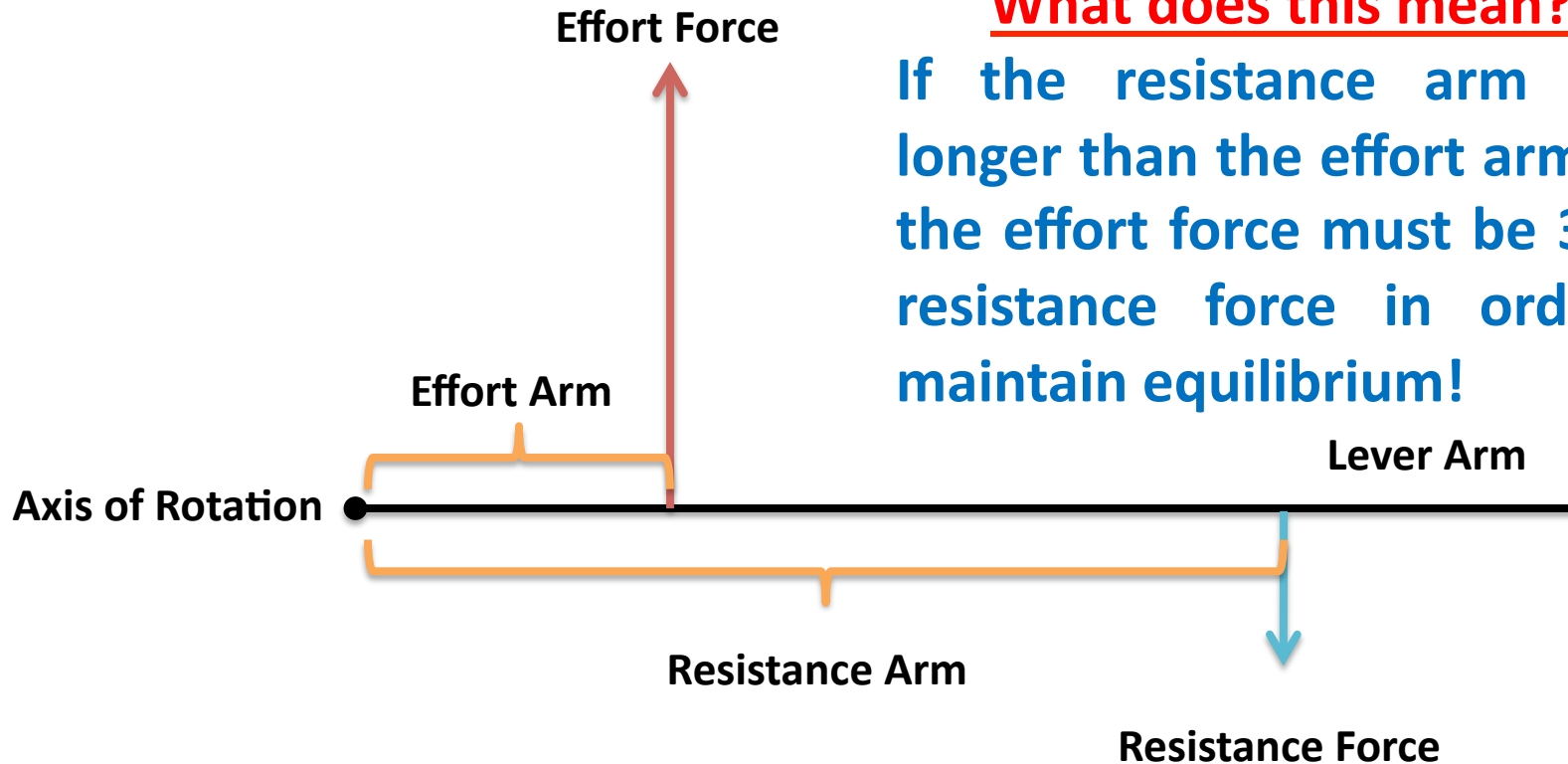
This image appears in Neumann DA: Kinesiology of the Musculoskeletal System:
Foundations for Physical Rehabilitation.
St. Louis, Mosby, 2002.

Copyright © 2002, Mosby, Inc. All rights reserved.

Mechanical Advantage

What does this mean???

If the resistance arm is 3x longer than the effort arm then the effort force must be 3x the resistance force in order to maintain equilibrium!

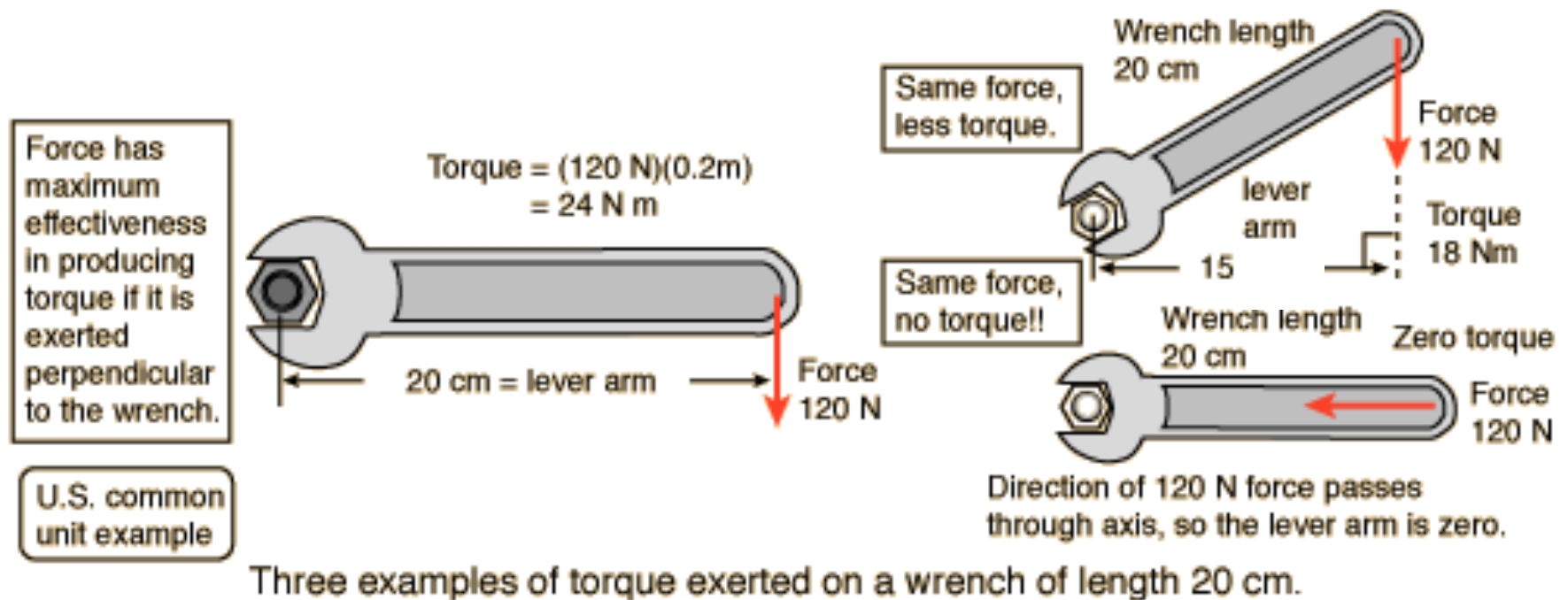


Effort Arm = 5cm
Resistance Arm = 15cm

$$MA_d = 5/15 = 1/3 = 0.33$$

What if force is applied at an angle other than 90°?

- Torque decreases as angle of application moves away from 90°
- No torque at either 0 or 180° (but maximal translational force)
- So $\tau = F \times D$ **only if** the angle is 90°



You can change torque by:

1. Changing force
 - Increase force, increase torque
 - Decrease force, decrease torque
2. Changing lever arm
 - Increase lever arm, increase torque
 - Decrease lever arm, decrease torque
3. Changing angle of force application
 - Move angle closer to 90° to increase torque
 - Move angle closer to 0° or 180° to decrease torque

Rules for Direction of Force Application

Closer to perpendicular (90°) equals more torque (rotary force)

Closer to parallel (0° or 180°) equals more translational (linear) force

Universal Equation to Calculate Torque

Accounts for Distance, Force and Angle

$$\text{Torque} = \text{distance} \times \text{force} \times \sin\theta$$

$$\sin 90^\circ = 1.0$$

$$\sin 60^\circ/120^\circ = 0.9$$

$$\sin 45^\circ/135^\circ = 0.7$$

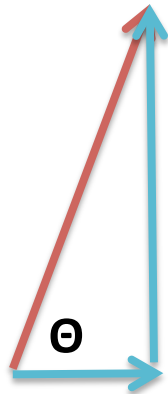
$$\sin 30^\circ/150^\circ = 0.5$$

$$\sin 0^\circ/180^\circ = 0$$

A 30° change in angle results in only a 10% change in force.

A 60° change in angle results in only a 50% change in force.

This is HUGE b/c most muscles insert at an angle closer to 0° than 90° !



A Note on Functional Movements

The angle of forces, both internal (muscles) and external (gravity, objects, etc.) ***constantly changes*** throughout the movement.

Therefore, we must always consider both forces ***at any given moment in time*** in order to manipulate the variables under our control and achieve the outcomes we desire.

This is critical for creating the most beneficial exercise interventions for our clients.

Clinical Applications

Manual Muscle Testing

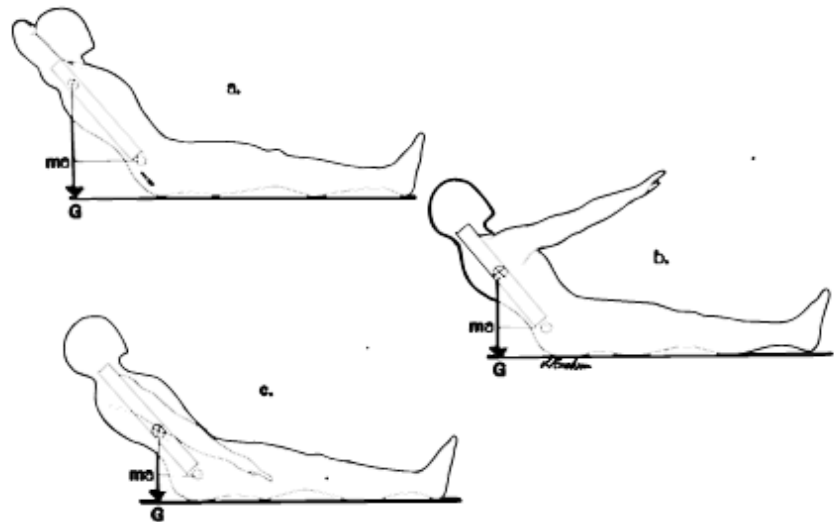


Distance from knee (Axis)?

Angle of force application?

Angle of tibia:femur?

Exercise Methods



Order from least resistance to most resistance.

Weight is not changing but the moment arm is increasing thus producing more torque and creating a biomechanical disadvantage for the muscles.

Compound Exercises

Multiple Joints = Multiple Torques

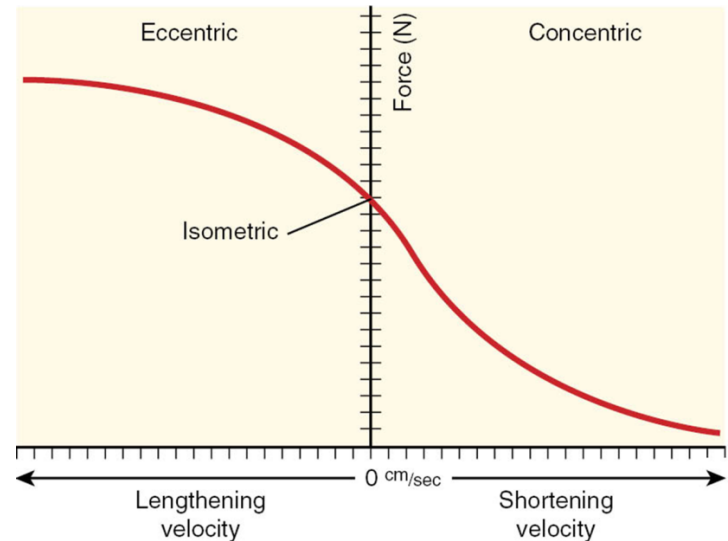
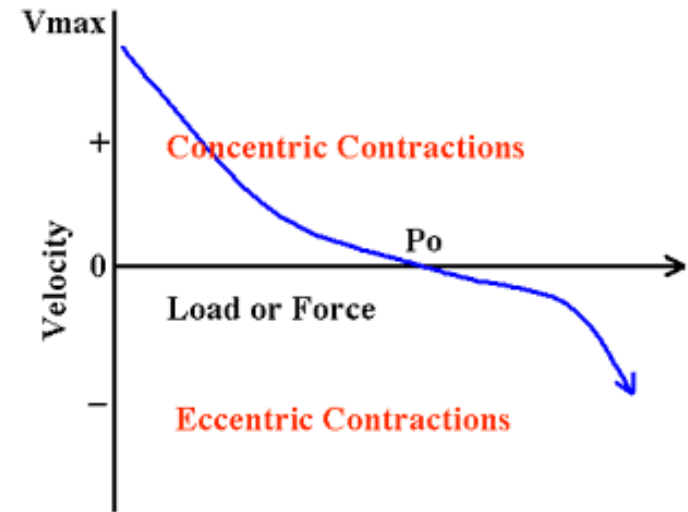


Types of Muscle Contraction

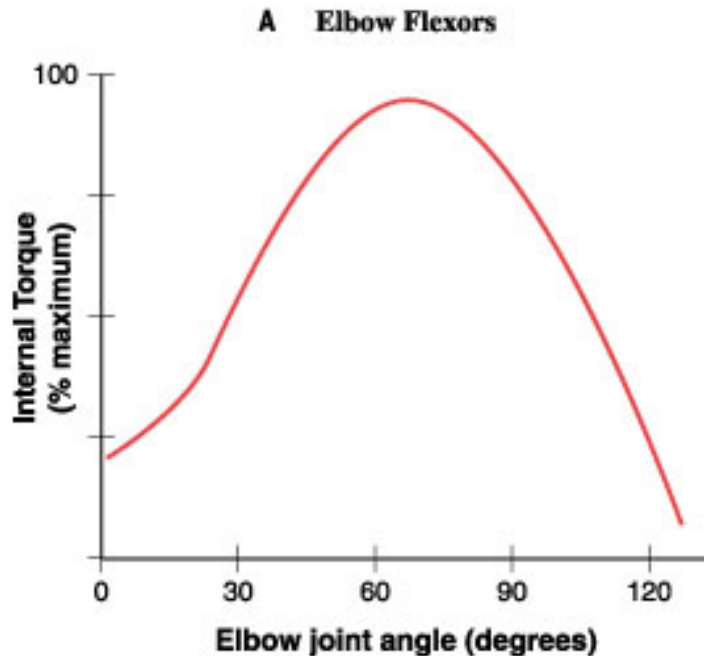
1. Isometric: muscle length does not change
 - No mechanical work is performed; no movement is produced; stabilizes joint position or posture; muscle work is performed; energy dissipated as heat (isometric heat production); initial isometric phase to all dynamic contractions; greater tension than concentric due to greater number of cross-bridges developed and activation of more motor units
 - Plank, wall squat, holding luggage
2. Concentric: muscle shortens
 - Muscle force greater than resistance force; “Up” phase of arm curl
3. Eccentric: muscle lengthens
 - Resistance force greater than muscle force; maximal tension developed (cross-bridges); “Down” phase of arm curl; walking down stairs; greater chance of producing DOMS (delayed-onset muscle soreness)
4. Ecentric: two-joint muscle that simultaneously uses isometric, concentric and eccentric contractions during functional tasks

Types of Contractions

- Eccentric contractions can produce greater force at similar (negative) velocities
 - Greater average force produced per cross-bridge as they are pulled apart
 - A more rapid reattachment phase of cross-bridge formation
 - Passive tension produced by the elastic components
- Isometric contractions at zero velocities

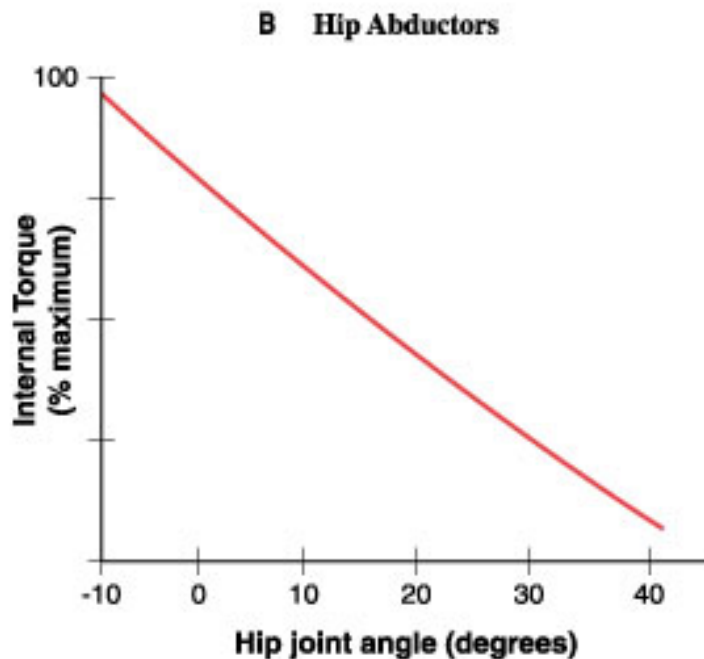


Copyright © 2010 by Mosby, Inc., an affiliate of Elsevier Inc.
(From Neumann: Kinesiology of the Musculoskeletal System, 2nd edition.)



Elbow Flexors

- Internal torque greatest at about 75°
- In the upright position the external torque caused by gravity is greatest in midranges of elbow flexion as well



Hip Abductors

- Internal torque greatest around 0°
- Similar angle at which the hip abductor muscles are most needed in the single-limb support phase of walking
- Rarely is maximal torque needed near maximal hip abduction so this matches its functional demands

Biomechanical Impact

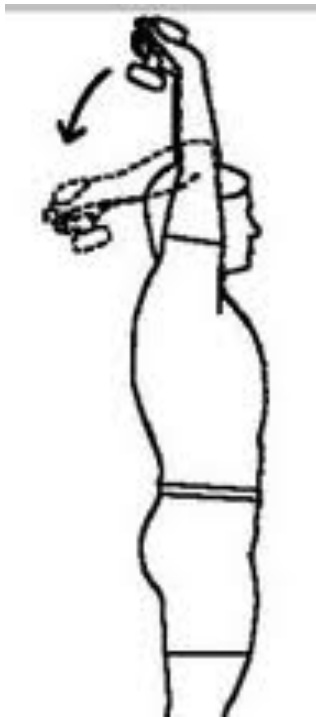
- Most (but not all) muscles produce their strongest contractions during the middle phase of their range of motion
- The moment arm of the muscle changes throughout the range of motion as does the moment arm of the resistance
- Gravity-based resistance depends on the limb's relationship to the line of gravity vector
 - Other forms of resistance depend on the limb's relationship to the line of resistance

Complex interactions between these three change dynamically throughout a movement

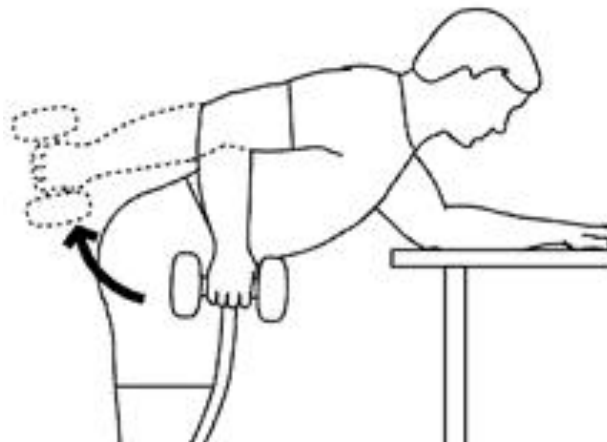
Triceps Extension

Notice how the different exercise movements create different internal and external torques at different angles

Overhead DB Extension



DB Kickback



Cable Extension

