Musculoskeletal Geometry

MCEN 4/5228

Modeling of Human Movement

Fall 2021

Musculoskeletal Geometry

- Muscle moment arm
- Moment arm definitions
  - Perpendicular distance
  - Tendon excursion
- Scaling and musculoskeletal geometry
- Summing muscle moments to predict strength
- Musculoskeletal geometry and architecture

Muscle moment arms

- Muscles actuate movement by rotating bones
- Muscle force converted from a force to a joint moment
- Muscles attach to bone at a distance from the joint – creating a torque at the joint.

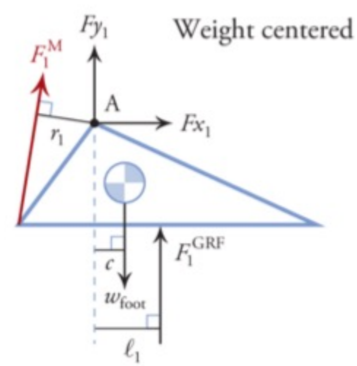
- A muscle's "moment arm" is the **perpendicular distance between the muscle line of action and the joint center**.

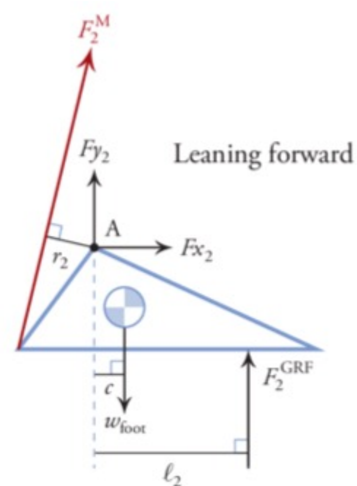
Muscle mechanical advantage

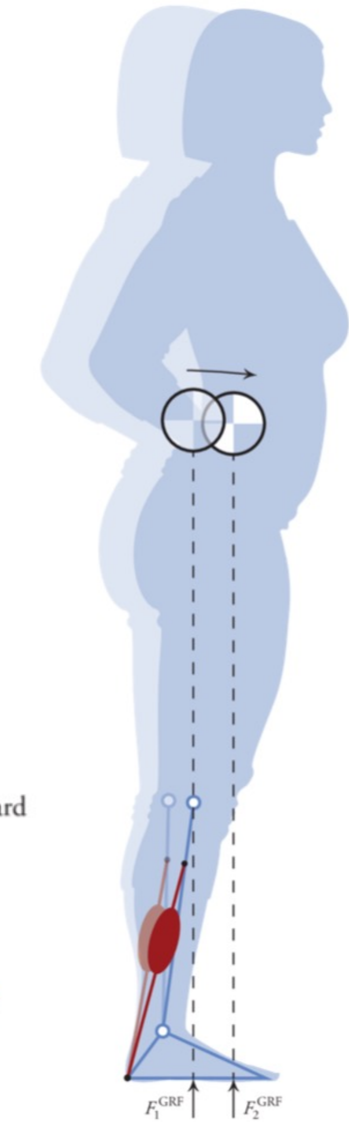
$$\sum M_A = F_i^{GRF}\ell_i - w_{foot}\,c - F_i^{M} r_i = 0$$

$$F_i^{M} = \frac{F_i^{GRF}\ell_i - w_{foot}\,c}{r_i}$$

Scenario	F_i^{GRF}	w_{foot}	ℓ_i	c	r_i	F_i^{M}
Weight centered ($i=1$)	600 N	7.8 N	5 cm	1 cm	5 cm	598 N
Leaning forward ($i=2$)	600 N	7.8 N	8 cm	1 cm	4 cm	1198 N







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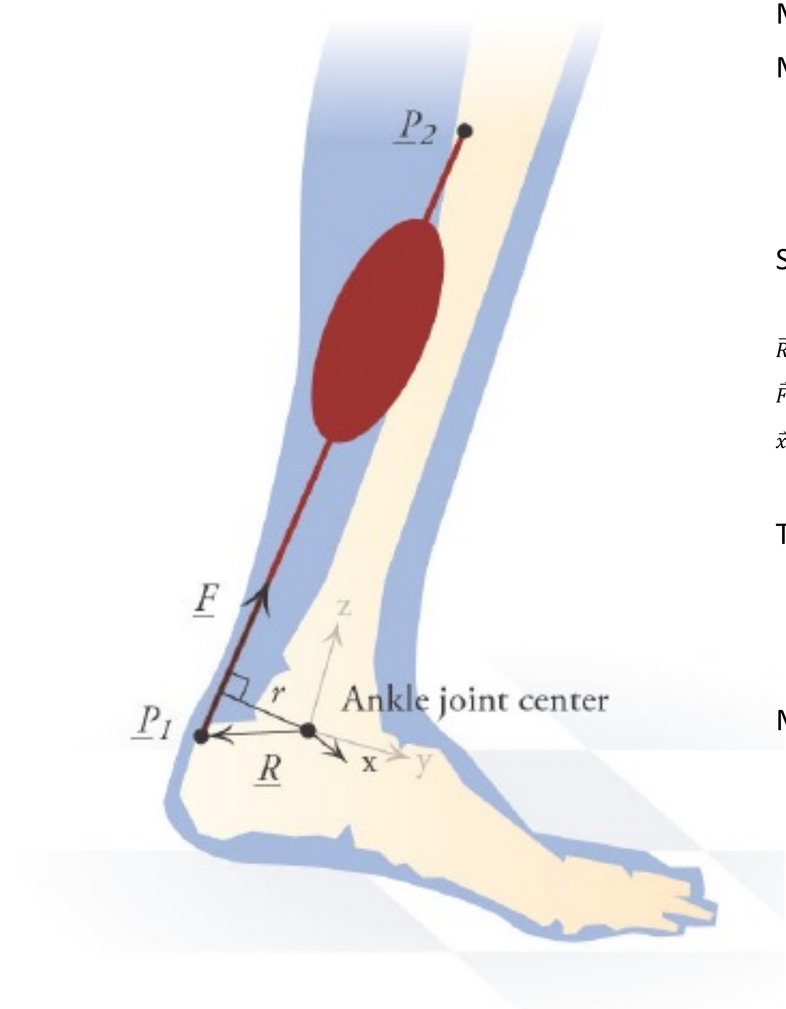
Perpendicular-distance definition

Figure 6.1



Moment arm is a scalar quantity, *r*

Multiply by magnitude of muscle force, $\|F\|$, to get moment about an axis

$$M_x = r\|F\|$$

Start with vector form:

$$\vec{M} = \vec{R}\times\vec{F}$$

$\vec{R}$: vector from the axis of rotation to the attachment point of the muscle

$\vec{F}$: magnitude and orientation of muscle force

$\vec{x}$: unit vector in the direction of the axis of rotation for the degree of freedom of interest

Therefore:

$$M_x = \left(\vec{R}\times\vec{F}\right)\cdot\vec{x}$$

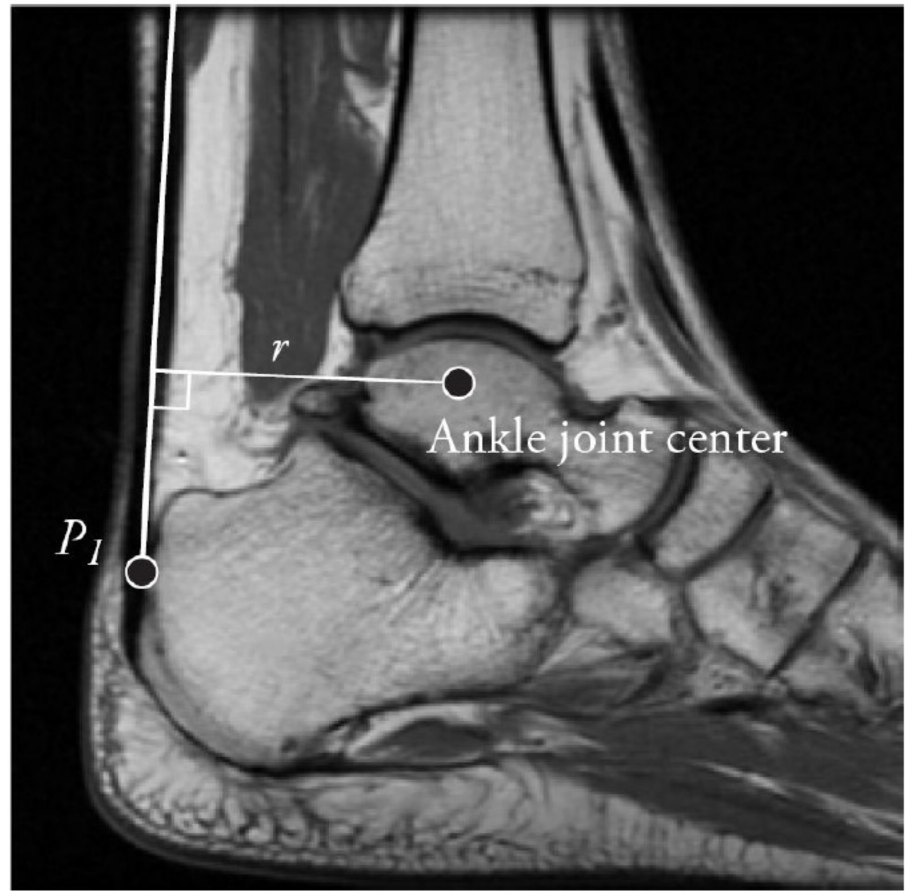
Moment arm defined by normalizing by $\|F\|$:

$$r = \frac{\left(\vec{R}\times\vec{F}\right)}{\|F\|}\cdot\vec{x}$$

How do you measure *r*?

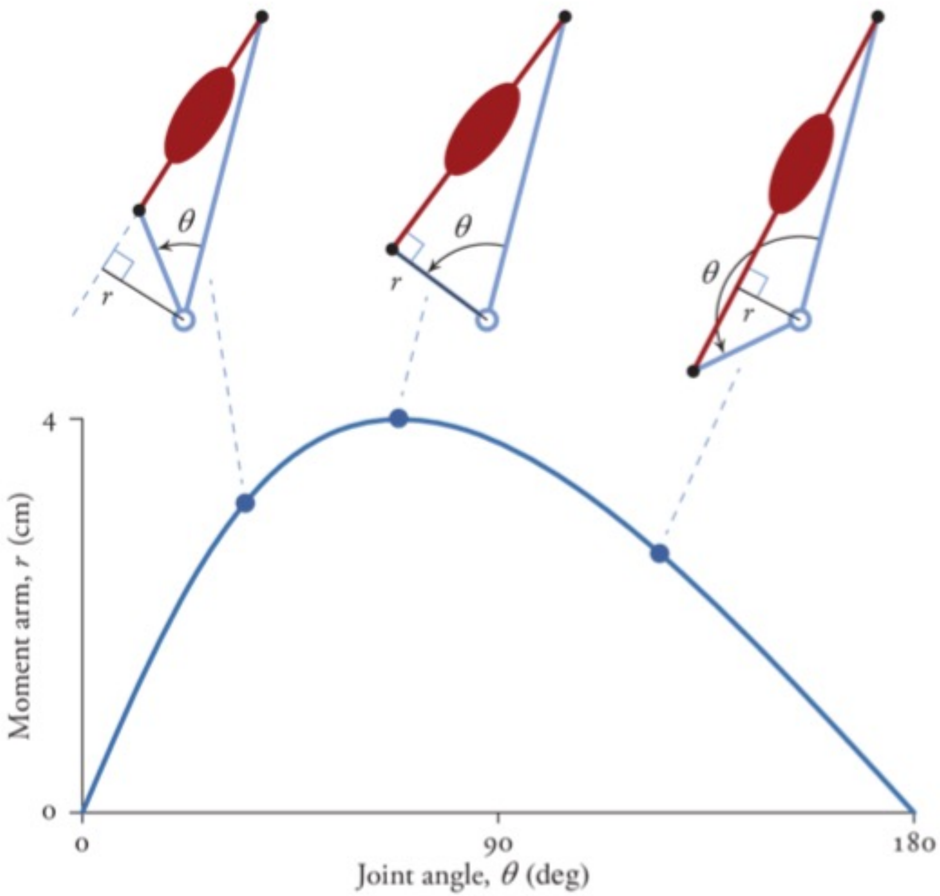
- Determine perpendicular distance from muscle line of action to the joint's axis of rotation

- MRI
- Ultrasound



$$M = r\,F^{\mathrm{MT}}$$

Moment arms vary with angle



For many muscles, relationship between moment arm and joint angle reaches a peak in the middle of the range of motion.

Tendon excursion definition

- Under certain assumptions is mathematically equivalent to the perpendicular-distance definition
    1. Moment arm is independent of muscle force
    2. Path of the muscle can be defined by a sequence of line segments
    3. Muscle tendon unit moves frictionlessly around neighboring structures

- Has important conceptual implications

Principle of virtual work

Total work done by all forces and moments acting on a system in static equilibrium is zero for a set of infinitesimally small "virtual displacements".

Virtual work done by a muscle:

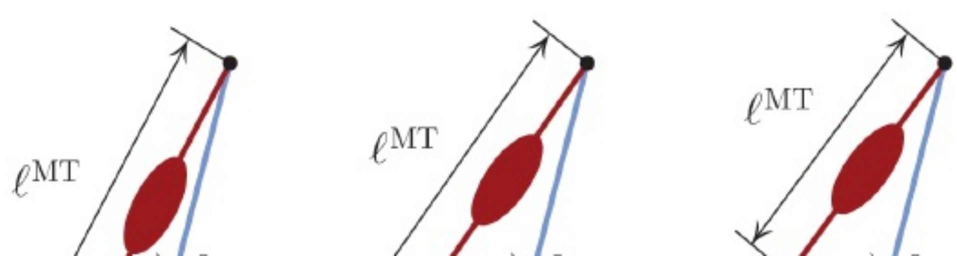
- Product of force generated by the muscle-tendon actuator and a virtual translational displacement, equivalent to change in length of the actuator

$$\delta w = F^{MT} \delta l^{MT}$$

Must be balanced by total work done by external moment:

- Product of external moment and virtual angular displacement of the joint

$$\delta w = M\delta\theta$$



Equate the two definitions

- Equation allows for moment arm measurement using the tendon displacement method

$$M\delta\theta = F^{MT}\delta l^{MT}$$

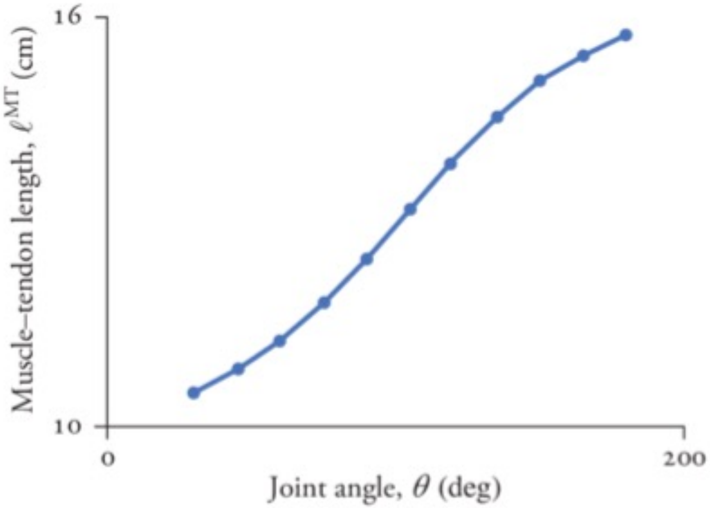
$$rF^{MT}\delta\theta = F^{MT}\delta l^{MT}$$

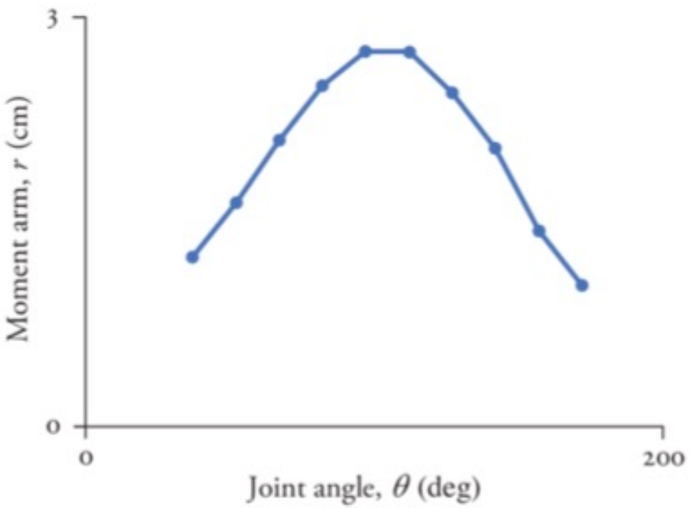
$$r = \frac{\delta l^{MT}}{\delta\theta}$$

- Measure joint angle and length of MTU simultaneously.

$$\boxed{r = \frac{\partial l^{MT}}{\partial\theta}}$$

Determine r experimentally

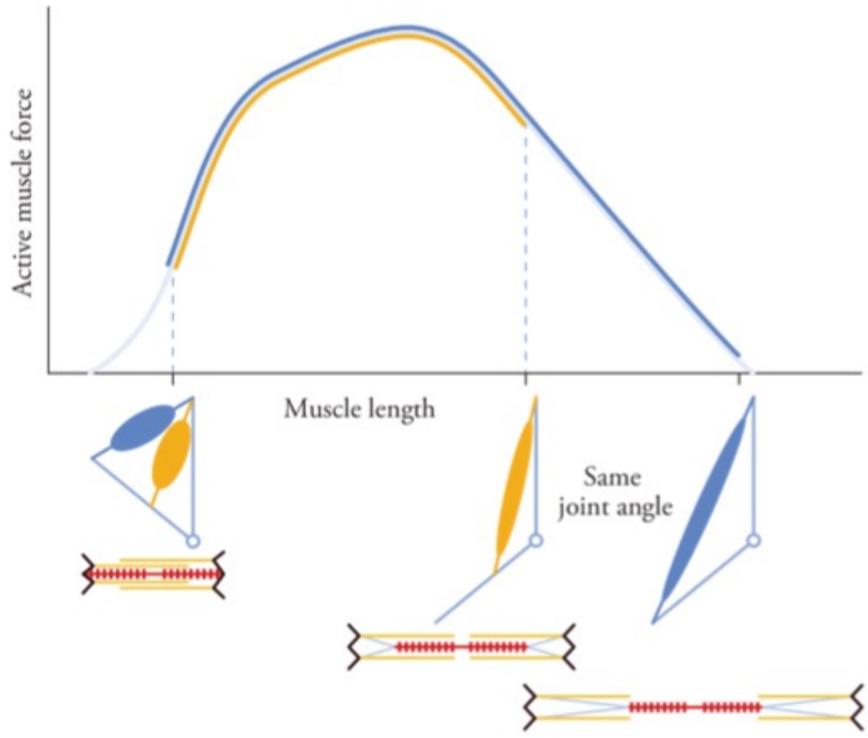




θ (deg)	ℓ^{MT} (cm)	$\Delta\theta$ (rad)	$\Delta\ell^{MT}$ (cm)	θ at midpoint (deg)	Moment arm (cm)
30	10.50				
45	10.82	$\pi/12$	0.32	37.5	1.22
60	11.25	$\pi/12$	0.43	52.5	1.64
75	11.80	$\pi/12$	0.55	67.5	2.10
90	12.45	$\pi/12$	0.65	82.5	2.48
105	13.17	$\pi/12$	0.72	97.5	2.75
120	13.89	$\pi/12$	0.72	112.5	2.75
135	14.53	$\pi/12$	0.64	127.5	2.44
150	15.06	$\pi/12$	0.53	142.5	2.02
165	15.44	$\pi/12$	0.38	157.5	1.45
180	15.71	$\pi/12$	0.27	172.5	1.03

Moment arm and F-L curve

Two muscles with the same optimal fiber length but different moment arms change length by different amounts and, therefore, traverse different ranges of the active force–length curve for the same range of joint angle.



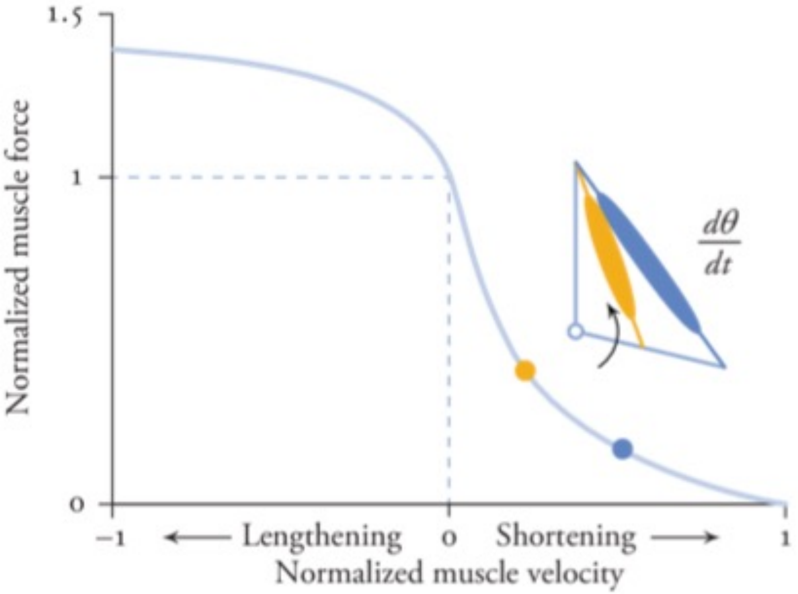
Moment arm and F-V curve

$$\left(\frac{\partial l^{MT}}{\partial \theta}\right)\left(\frac{\partial \theta}{\partial t}\right) = r\,\frac{\partial \theta}{\partial t}$$

$$\frac{\partial l^{MT}}{\partial t} = v^{MT} = r\,\frac{\partial \theta}{\partial t}$$

- For the same angular velocity, muscles with larger moment arms experience higher *in vivo* contraction velocities.

- Muscles with larger *r* will shorten at higher velocity, lowering active muscle force.



Moment arm trade-offs

- Larger moment arm → larger joint moment
- Larger moment arm → larger excursion/velocity

- Leads to substantial variation among muscles that cross each joint.

- Perhaps joints with high angular velocities need small moment arms?

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- Perhaps joints with high angular velocities need small moment arms?
  - Elite sprinters have smaller Achilles tendon moment arms than size-matched non-sprinter controls. (Lee and Piazza, 2009)

Lee SSM and Piazza SJ 2009 Built for speed: musculoskeletal structure and sprinting ability. Journal of Experimental Biology 212(22): 3700-3703

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Scaling and musculoskeletal geometry

- Do moment arms scale with anatomical size?
  - Murray et al. 2002
    - In elbow flexors and extensors, distance between the elbow joint center and muscle attachment correlated with humerus length and individual's height.

Murray WM, Buchanan TS, Delp SL 2002. Journal of Biomechanics 35(1):19-26

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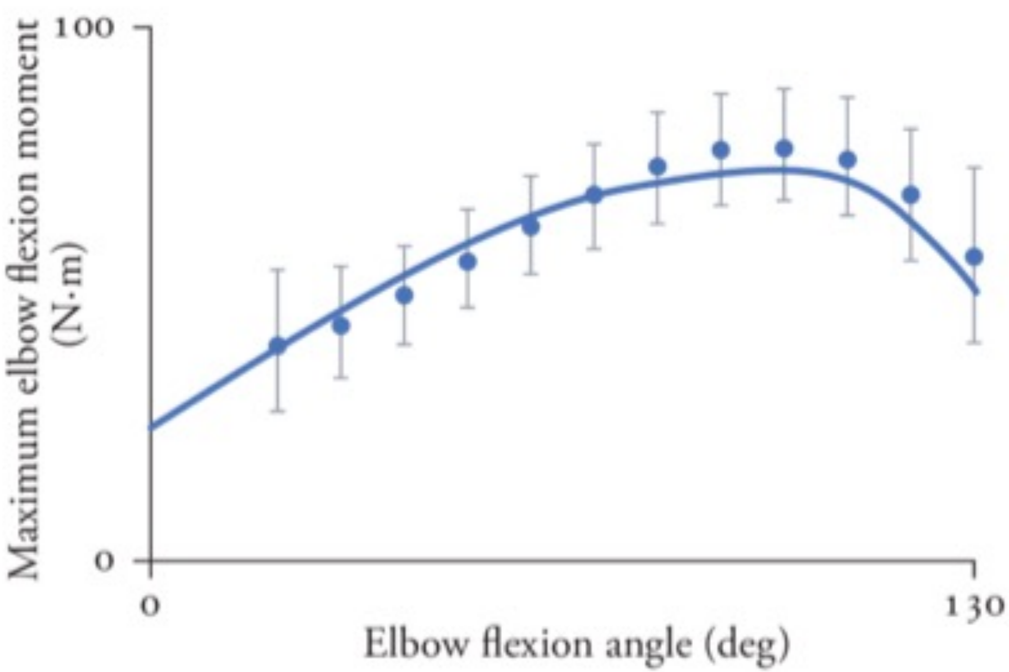
Predicting joint strength

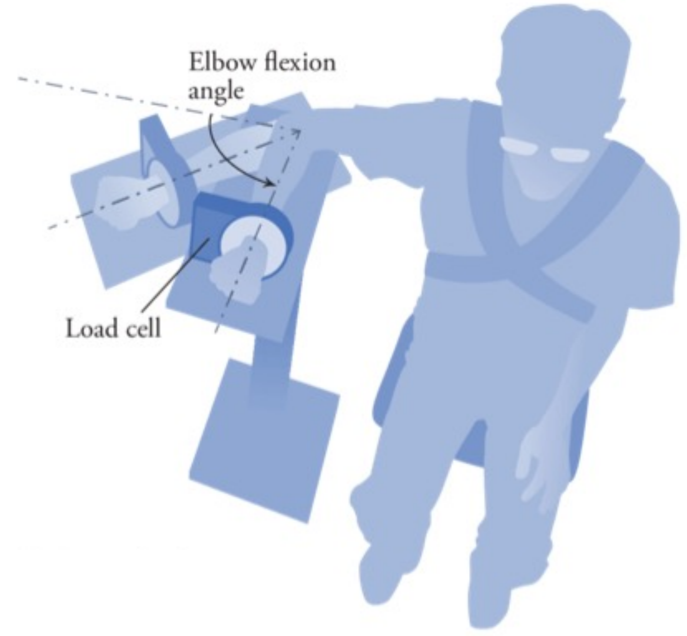
- Strength depends on multiple factors
  - Many muscles act across a joint
  - Moment of each will depend on
    - Joint angle
    - Muscle force

  - Maximum joint moment that can be generated at a given joint angle is the product of the moment arm and the maximum force that can be generated at that angle.
  - Total muscle moment for the entire joint is computed by summing the moment-vs-angle curves for all muscles

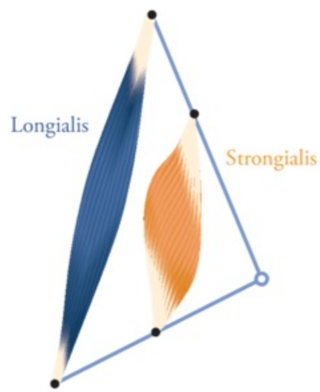
→ maximum voluntary isometric moment for the joint (which we can measure!)

Maximum isometric elbow moment

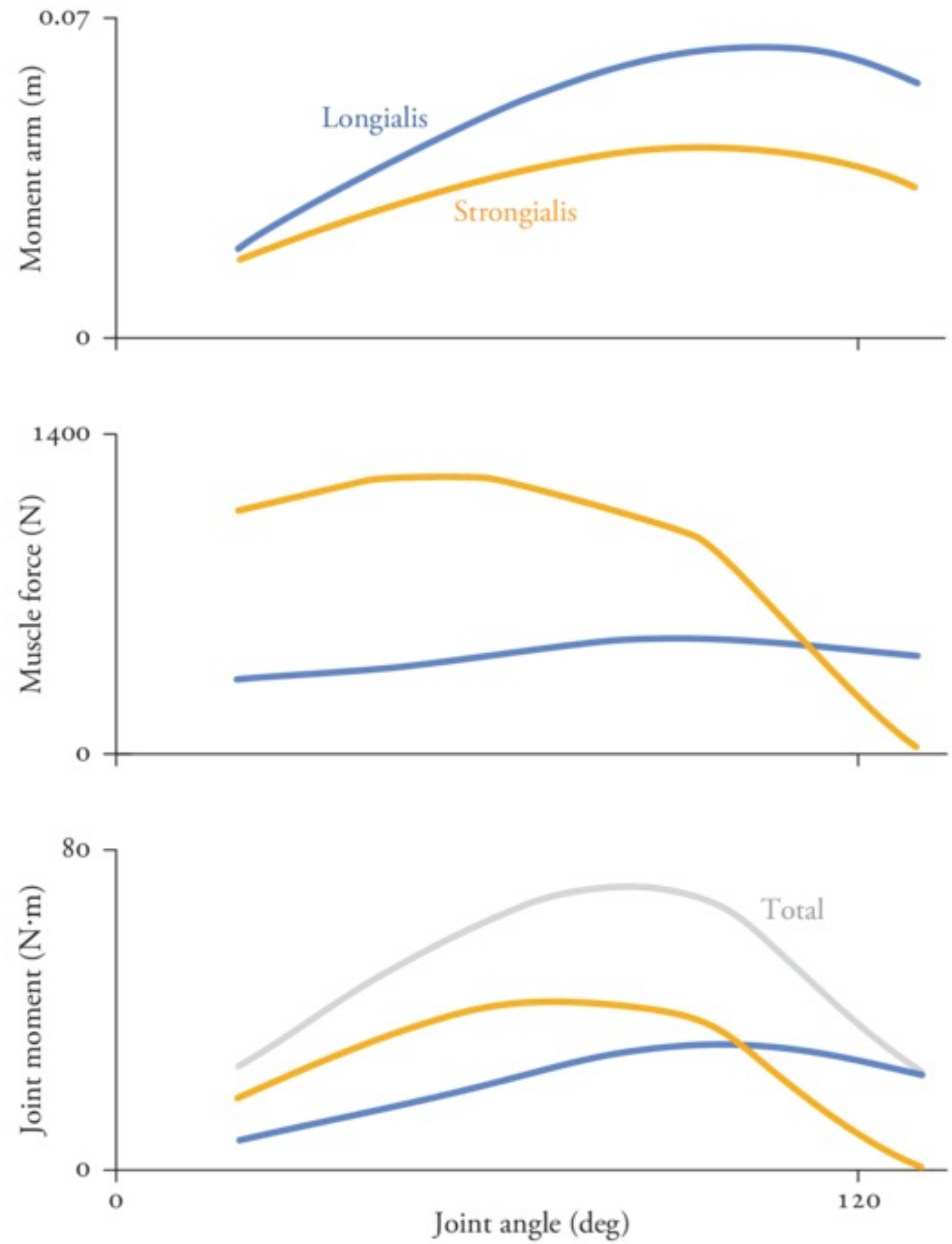




A tale of two muscles



- "Longialis"
  - Long fibers
  - Smaller PCSA
  - Larger moment arm
- "Strongialis"
  - Short fibers
  - Large PCSA
  - Smaller moment arm
- Note: Peak joint moment



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MS geometry and architecture

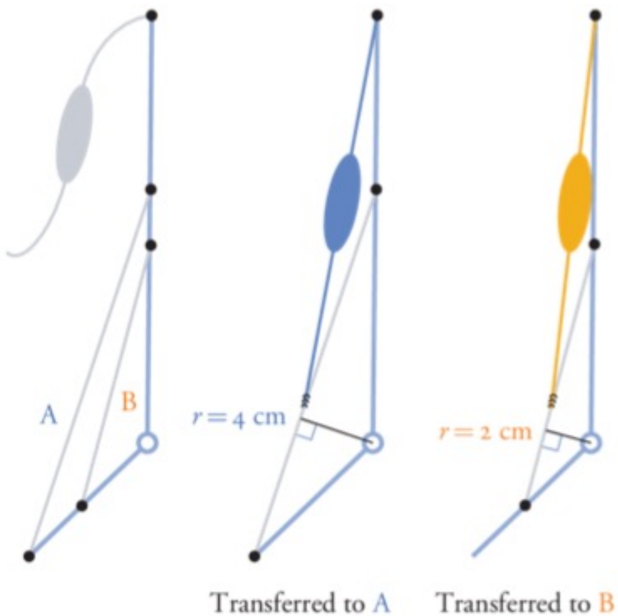
- Muscle moment depends on both muscle force and moment arm

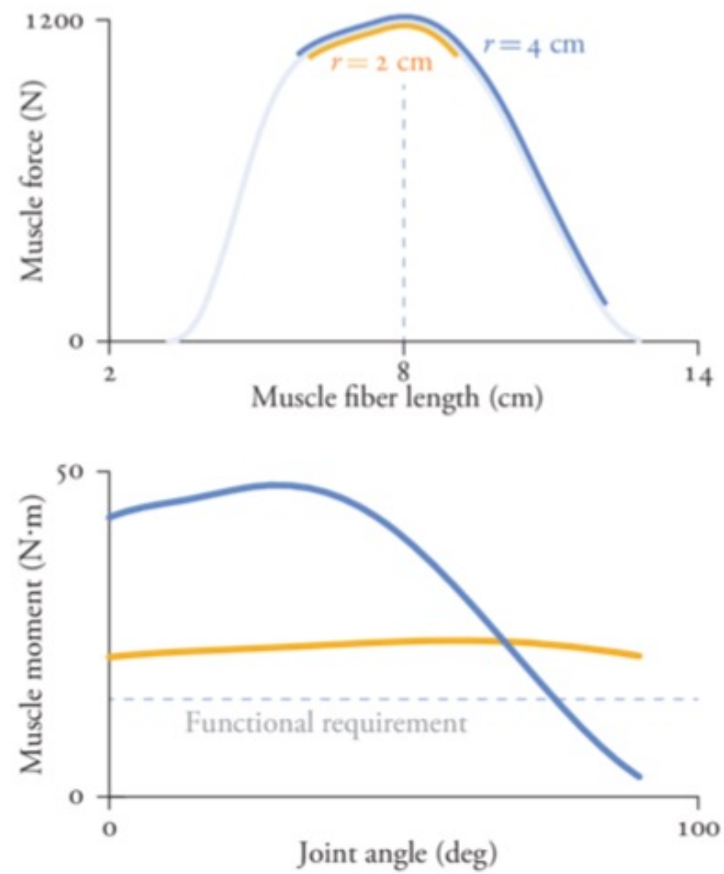
- If muscle has a large moment arm and must generate active force over a large range of motion, it would require …

MS geometry and architecture

- Muscle moment depends on both muscle force and moment arm
- If muscle has a large moment arm and must generate active force over a large range of motion, it would require …
- Useful to quantify ratio of muscle moment arm to the optimal fiber length.
- Generally, muscles with larger moment arms have longer fibers.

Tendon transfer example





- Where to attach functioning muscle?
- Tendon of muscle A or muscle B?
- Req: Min Torque of 15Nm over 90º range

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