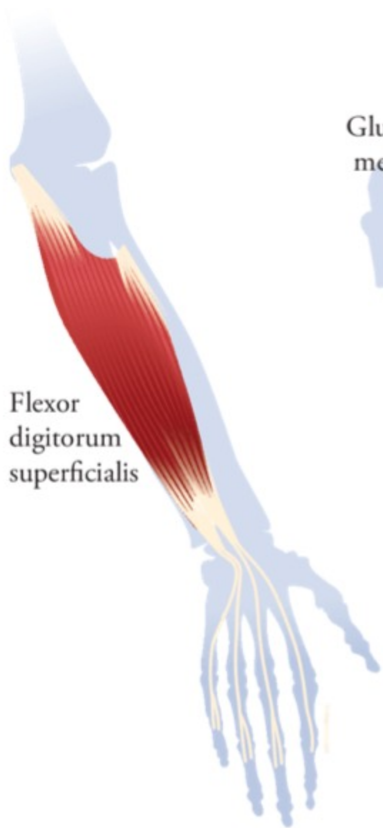
Musculotendon Architecture and Dynamics

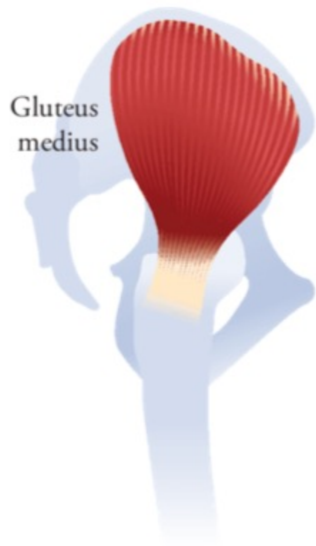
MCEN 4/5228

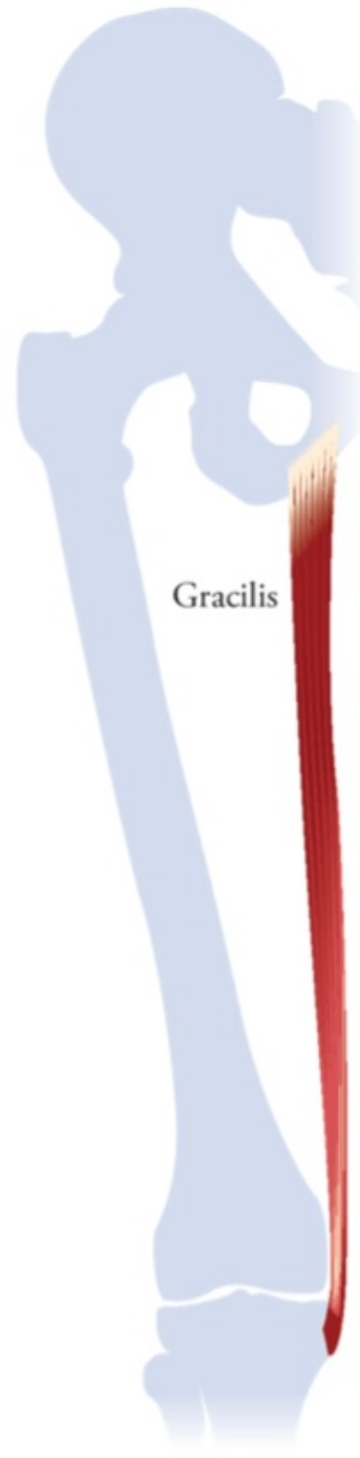
Modeling of Human Movement

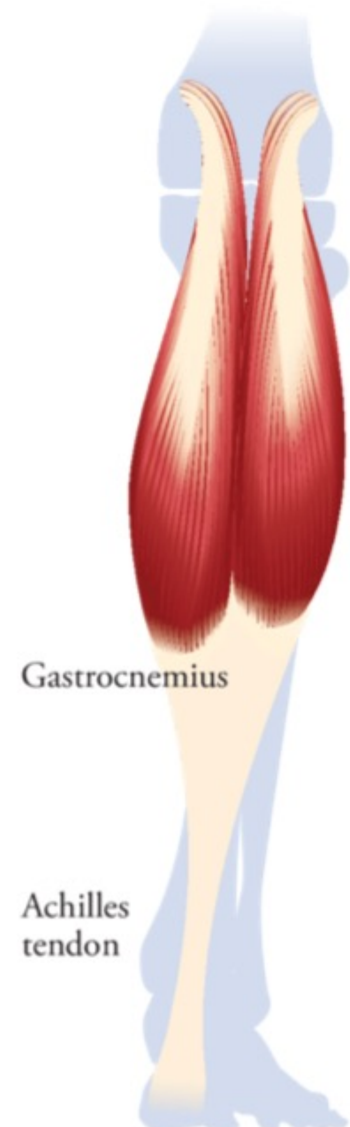
Fall 2021

Muscle architecture and function vary throughout the body









Musculotendon Dynamics

- Muscle Fiber Architecture
  - Series/Parallel
  - Pennation angle
- Muscle-Specific Parameters
  1. Optimal muscle fiber length
  2. Muscle fiber pennation angle
  3. Maximum isometric muscle force
  4. Maximum muscle contraction velocity
  5. Tendon slack length
- Measuring Muscle Specific Parameters
- Hill-type Muscle Model

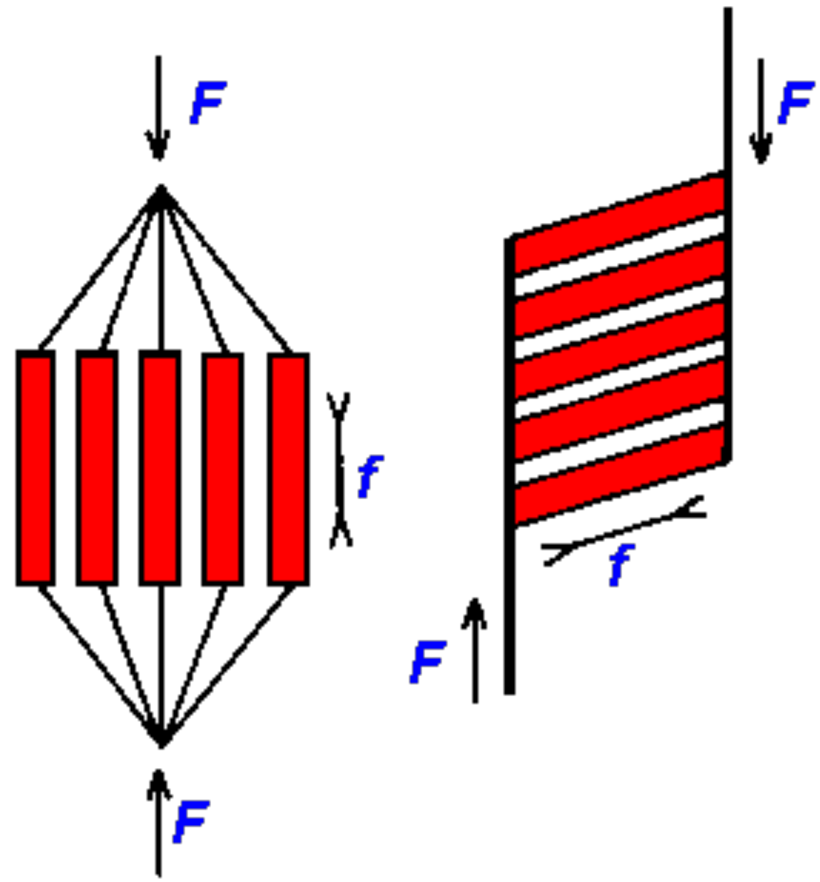
Muscle fiber architecture

- Organization of muscle fibers
  - Muscle also organized at macro level
  - Architecture is the arrangement of muscle fibers relative to the axis of force generation
  - Muscle fibers have fairly consistent diameters among muscles of different size, but arrangement can be very different

Muscle fiber architecture

- Parallel fibered muscles
- Pennate fibered muscles

- Sarcomeres in parallel
  & in series
- Strength vs. speed



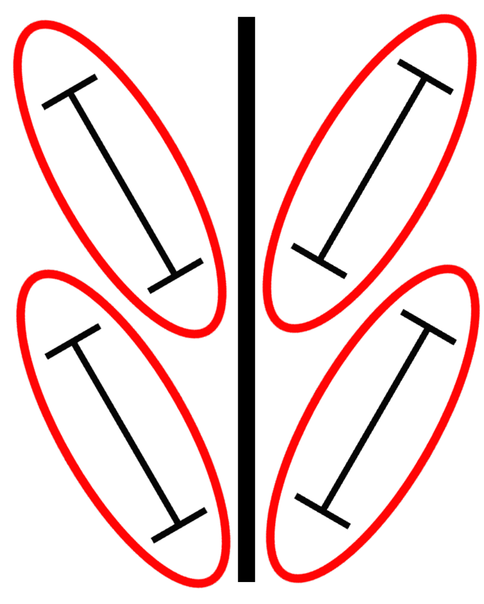
Muscle architecture

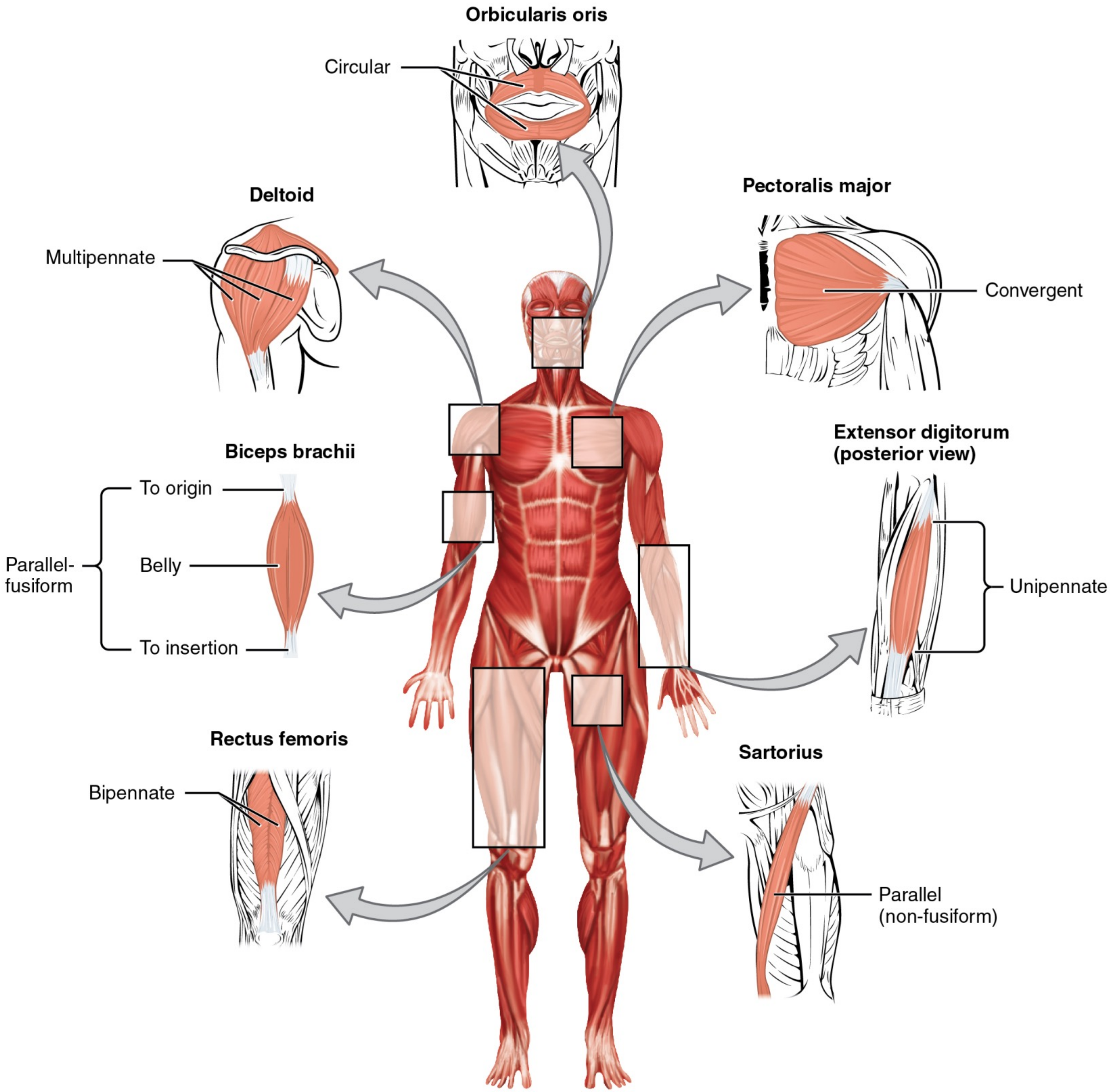
- Determines
  - Maximum muscle force
    - Fibers in parallel
    - Pennation angle
  - Maximum muscle shortening velocity
    - number of sarcomeres in series

- Series:high excursion
- Parallel:high force
- Strength vs Speed

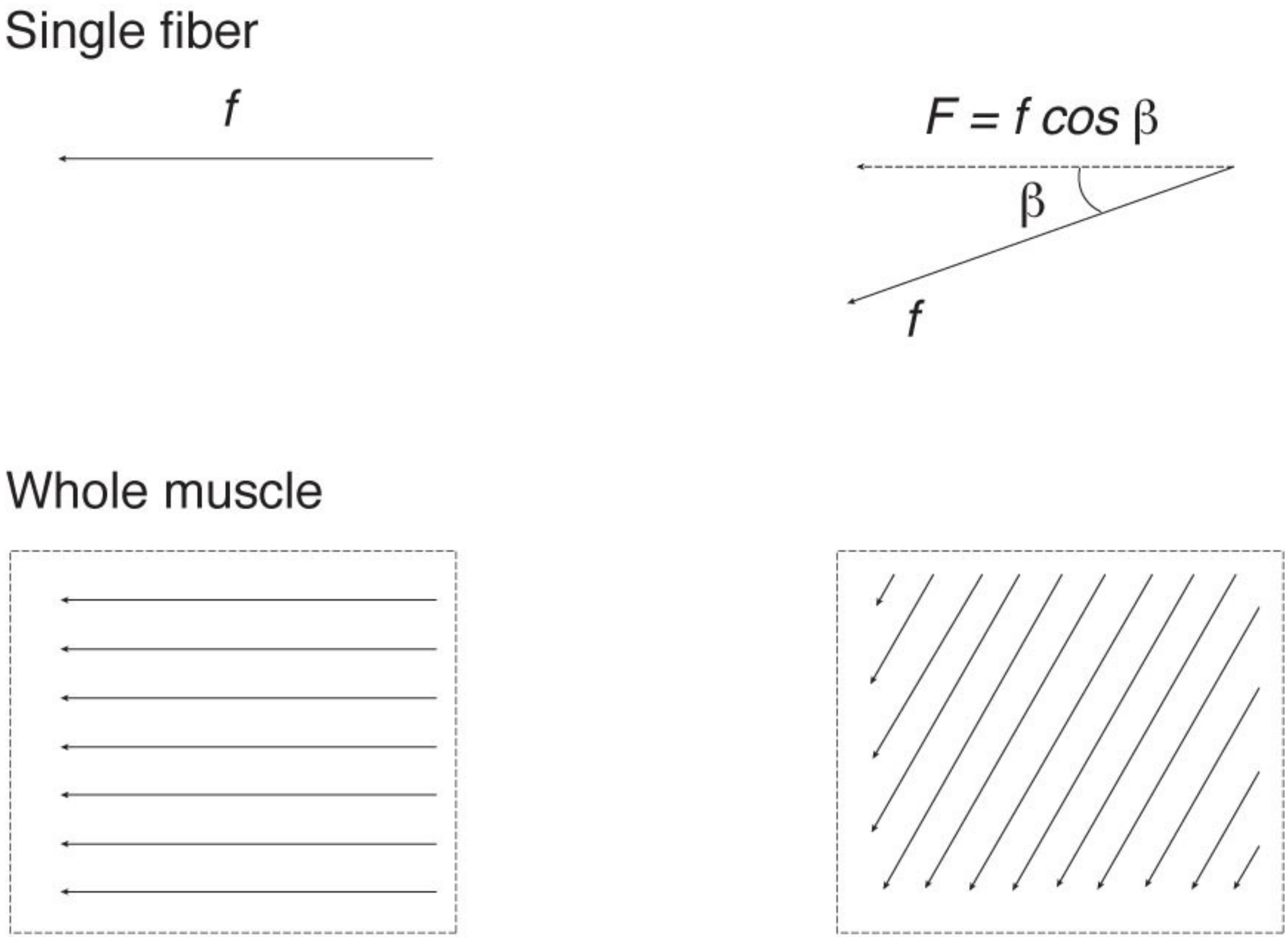
Pennate muscles

- Fascicles form common angle with the tendon
- Muscle cells pull at an angle



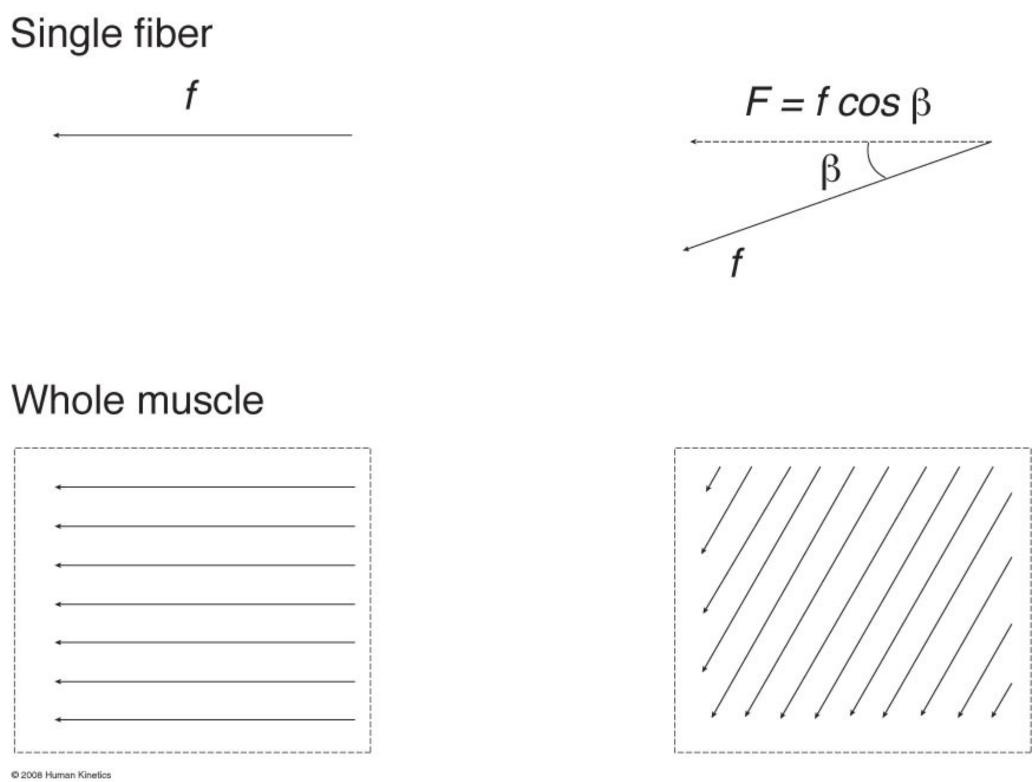

Orbicularis oris
Circular
Deltoid
Multipennate
Pectoralis major
Convergent
Biceps brachii
To origin
Belly
To insertion
Parallel-
fusiform
Extensor digitorum
(posterior view)
Unipennate
Rectus femoris
Bipennate
Sartorius
Parallel
(non-fusiform)

Pennation Angle



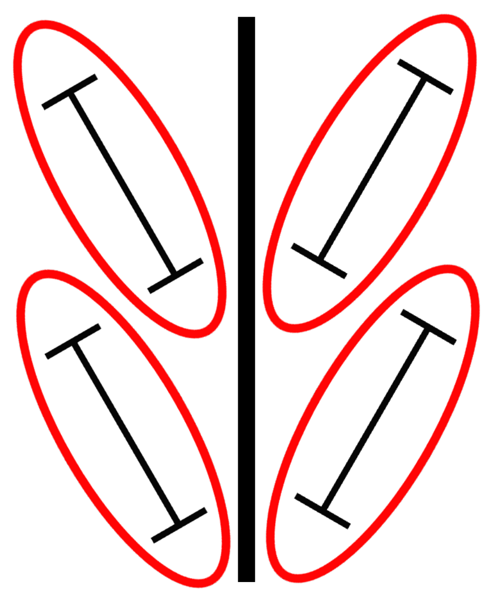
Pennation Angle

- Pennation angle is a space saving strategy
- Allows you to pack more fibers into a smaller space
- Doesn't hurt because $\cos 0^{o}=1$, $\cos 30^{o}=0.87$ (13% force loss)



Pennate muscles

- Fascicles form common angle with the tendon
- Muscle cells pull at an angle
- Contraction **doesn't move as far** as series muscles
- Contains more muscle fibers and, as a result, **produces more force** than a parallel muscle of the same size



Muscle architecture

- Determines
  - Maximum muscle force
    - Fibers in parallel
    - Pennation angle
  - Maximum muscle shortening velocity
    - number of sarcomeres in series

Muscle fiber length

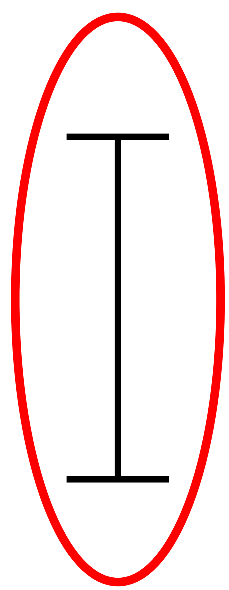
- Assumed that fiber length ~fiber velocity
- Fiber length ~ number of sarcomeres in series

Muscle Design Problems: Setup

1 muscle fiber

Force = f

Velocity = Δl/s = v

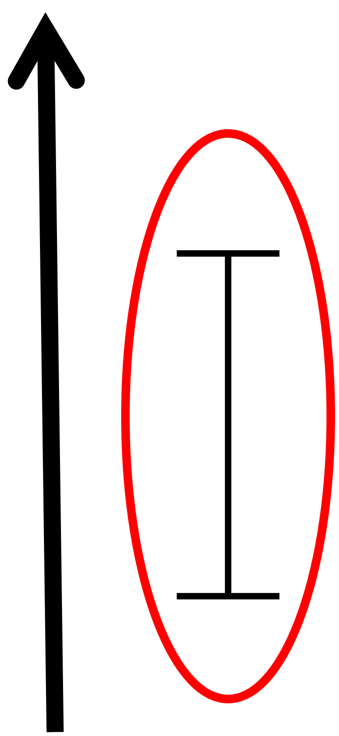


Muscle Design Problems: Setup

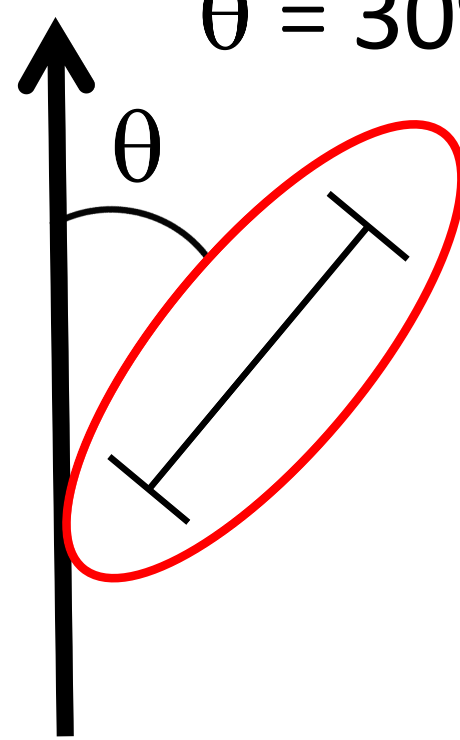
1 muscle fiber

Force = f

Velocity = Δl/s = v



$\theta = 30^{o}$



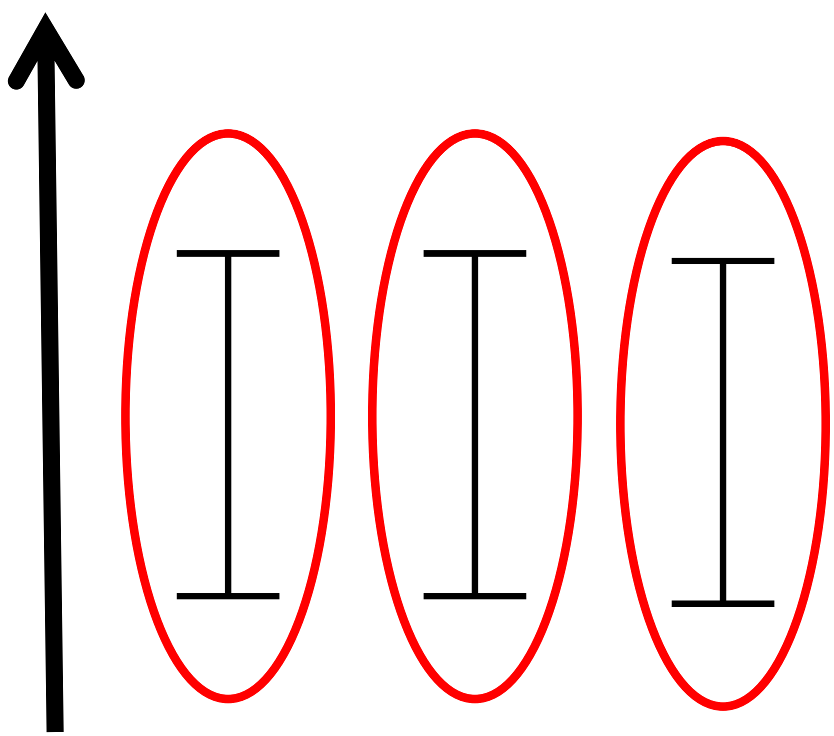
Determine the force
& velocity

Muscle Design Problems: Setup

3 muscle fibers

Force = f

Velocity = Δl/s = v



Determine the force & velocity

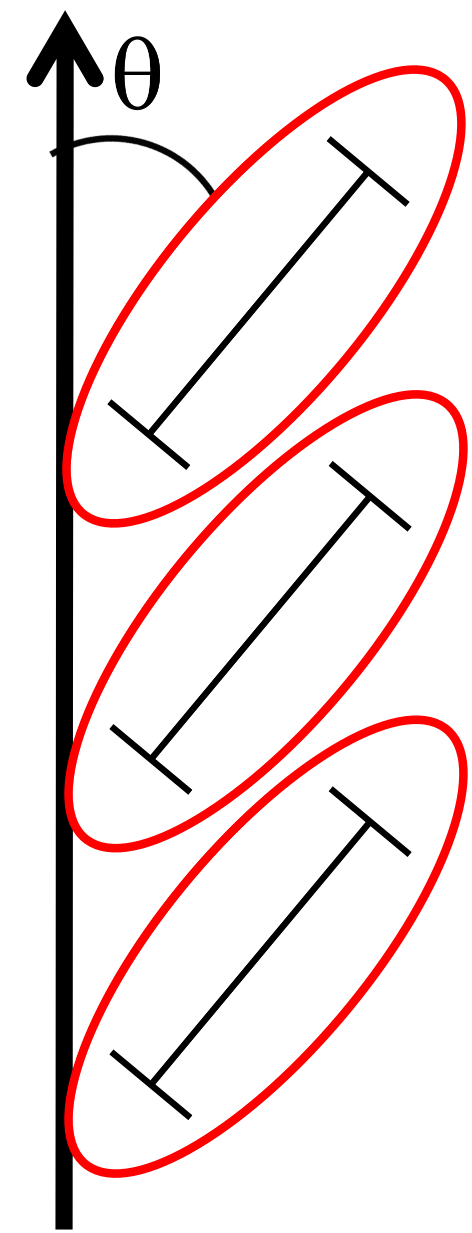
Muscle Design Problems: Setup

3 muscle fibers

Force = f

Velocity = Δl/s = v

θ = 30°



Determine the force & velocity

Musculotendon Dynamics

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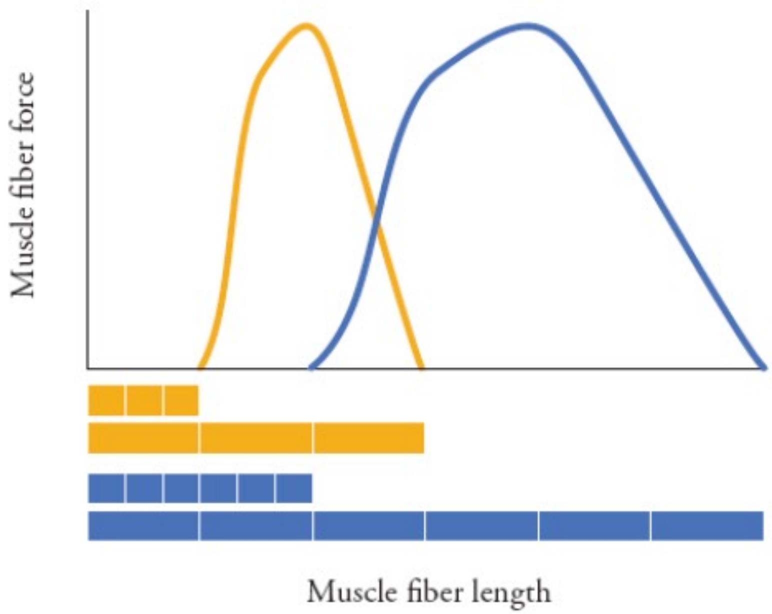
1. Optimal muscle fiber length, l_o^M :

- Sarcomere optimal length: the length at which a sarcomere can develop maximum isometric force

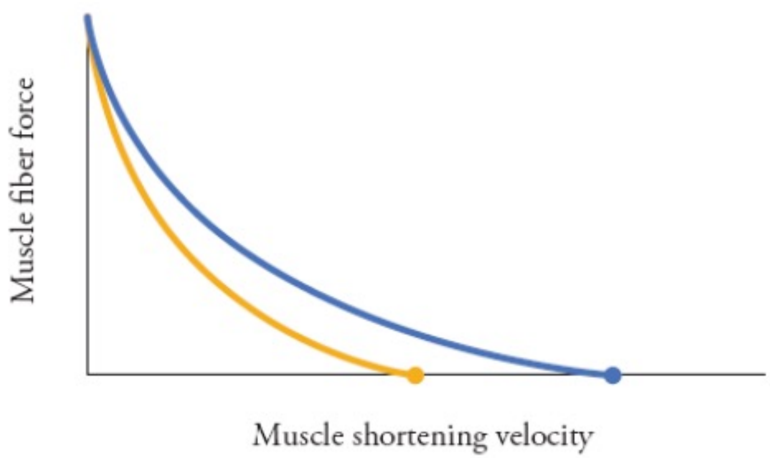
- Muscle fiber optimal length: when each of the muscle's sarcomeres is at its optimal length

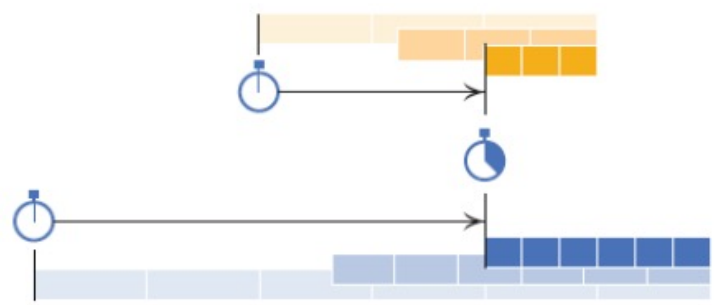
$$l_o^M = \text{number of sarcomeres in series} \times \text{optimal sarcomere length}$$

Effects of muscle length



- Longer muscles have more sarcomeres in series
  - Broader active force length curves
  - Higher maximum shortening velocities (v^M_{max})

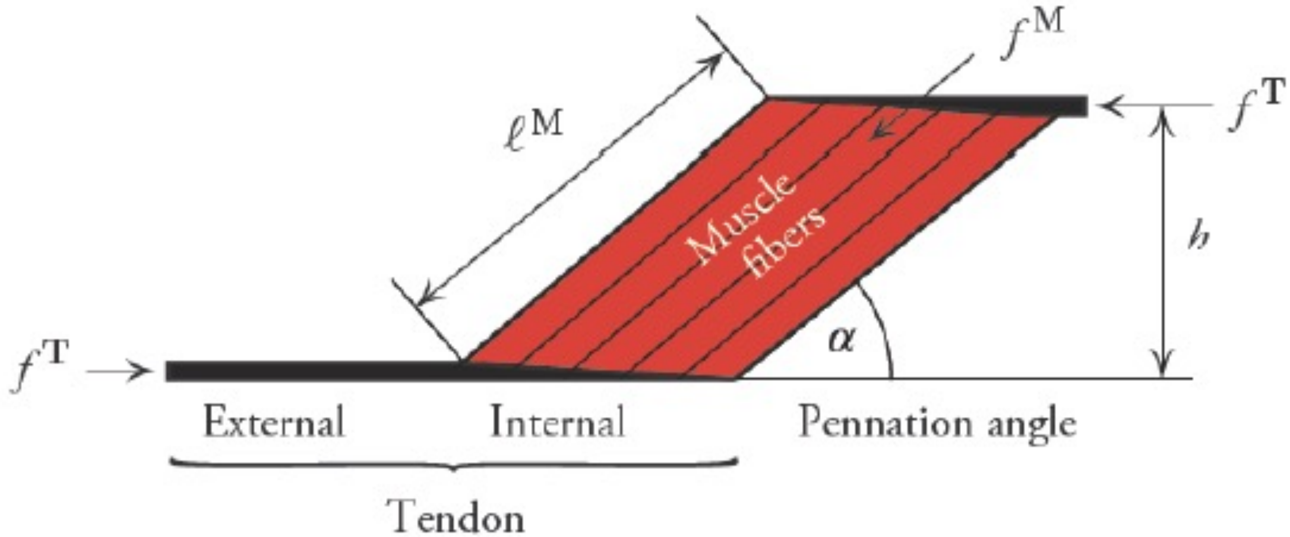




2. Muscle fiber pennation angle at optimal fiber length, α_o

- Relationship between force in muscle fibers and tendon :

$$f^T = f^M \cos(\alpha)$$



Effect of pennation

- Increases the number of fibers that can be packed into a given volume

3. Maximum isometric muscle force

- The number of fibers in muscle determines maximum active force.
- In a parallel fibered muscle, cross-sectional area is a good estimate of the number of fibers.
- In a pennate muscle, must use area of section taken perpendicular to the fiber: *the physiological cross-sectional area (PCSA)*

$$f_o^M = PCSA * \sigma^M$$

σ^M is the muscle's specific tension (peak isometric stress)

Typically modeled as σ^M=0.3MPa

More on PCSA

- NOT proportional to
  - muscle mass
  - muscle volume
  - *anatomical* cross-sectional area

3. Maximum isometric muscle force

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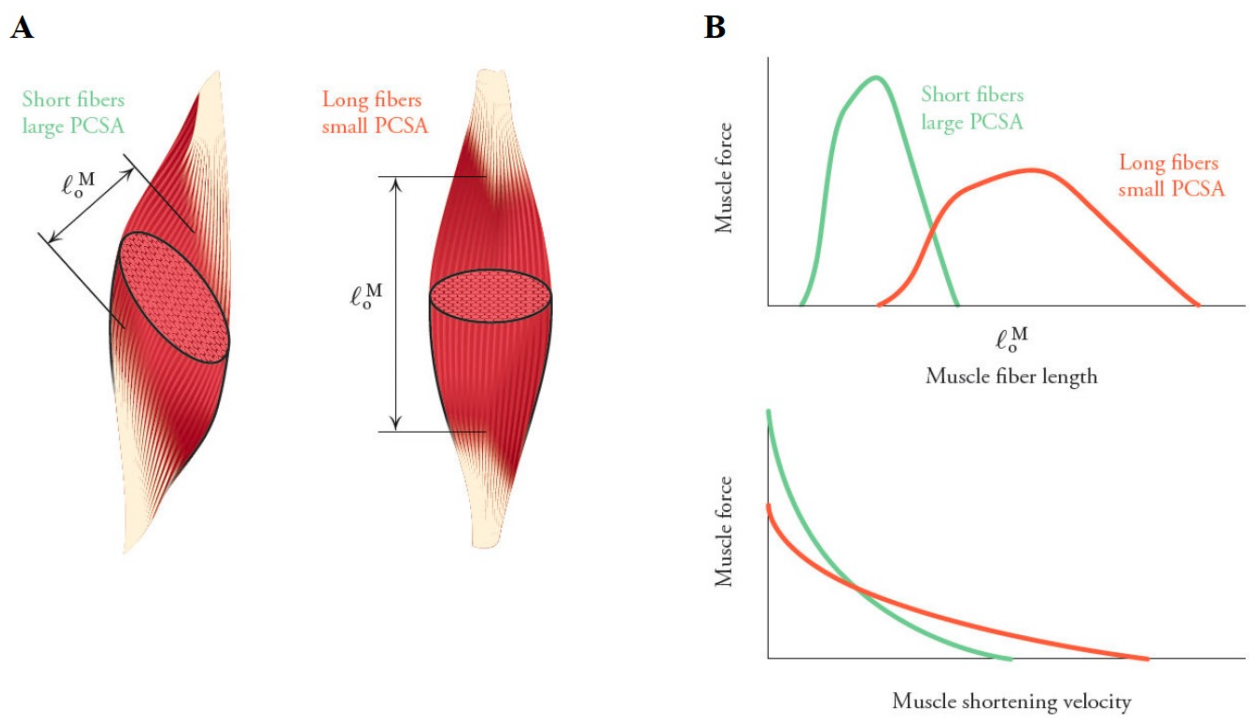
Two muscles of the same volume:



4. Maximum muscle contraction velocity, v_{max}^{M}

- Muscles fibers can be of different types
  - Determined by myosin form
  - Fast-twitch: $10l_o^M/s$
  - Slow-twitch: $3l_o^M/s$

  - All fibers in a motor unit are of the same type
  - BUT a muscle can have motor units of different types

5. Tendon slack length, l_s^T

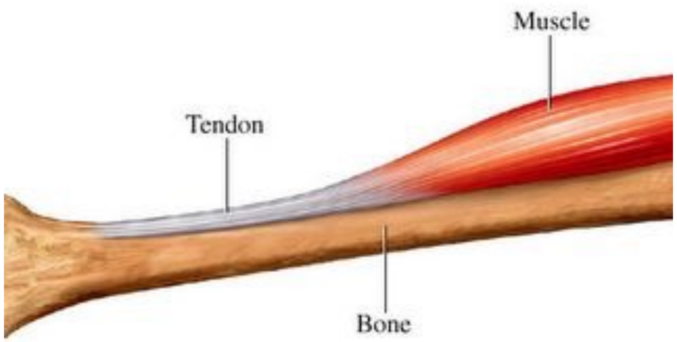
J Appl Physiol 103: 423–424, 2007;
doi:10.1152/japplphysiol.00426.2007.

Tendon mechanics: the argument heats up

TENDON has long been undervalued. Most textbooks describe only one concept of this tissue: tendons attach muscles to bones. This is akin to saying that Michelangelo was a painter. Both statements are true but do not even begin to describe the importance of their subjects. In fact, tendons play an essential role in a number of physiological processes, including decreasing muscle injury (8), and, in humans, provided an evolutionary advantage for bipedal gait (3). Given this background, a deeper insight into tendon mechanics is long overdue.

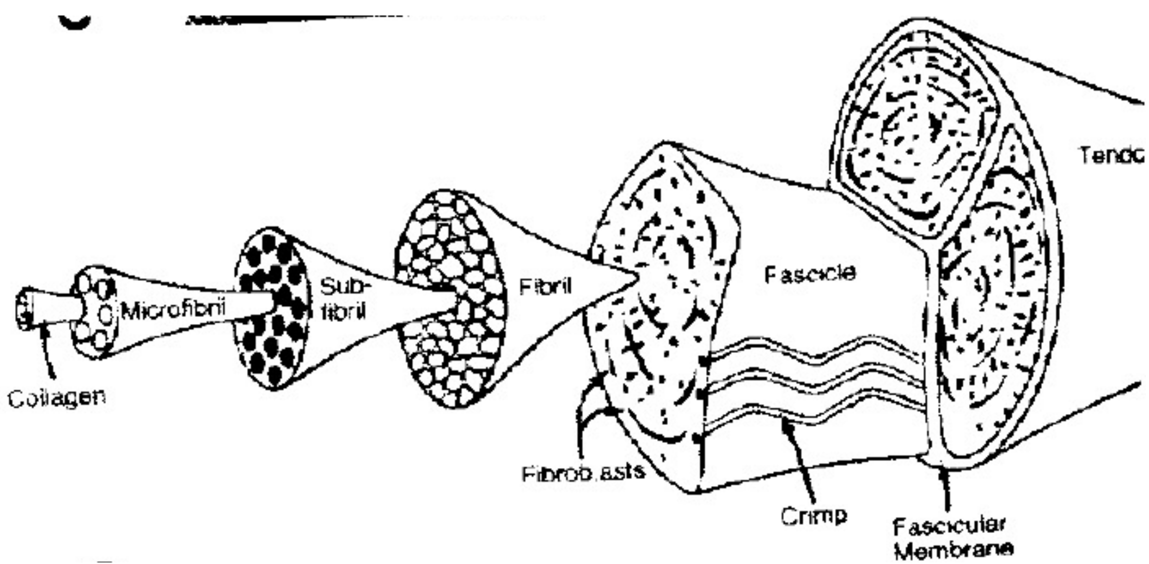
Machinery of Movement

- Skeleton
  - Lightweight, approximately rigid structure
  - Supports tension, compression, bending
  - Articulated joints: degrees of freedom
- Muscle
  - Active force and work performing tissue
  - Supports tension
  - Dynamic behaviors
- Tendon
  - Interface between muscle and bone
  - Highly compliant
  - Low hysteresis
  - Passive
  - Stores elastic energy



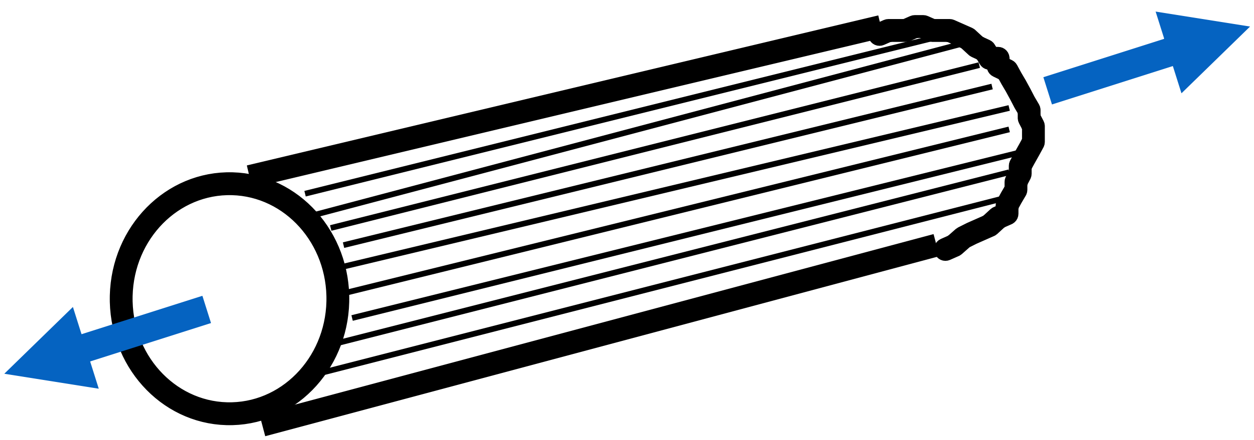
Structure

- Primarily collagen : a structural protein
- Collagen fibril -> fascicle->tendon
- Bad blood supply -> slow to heal



Structure

- Parallel bundles of collagen fibers
- Resist stretching along long axis of tendon
- Sufficiently flexible



Mechanical Properties

- Many experiments on isolated tendons
- Show *same* mechanical properties across different tendons

Mechanical Properties

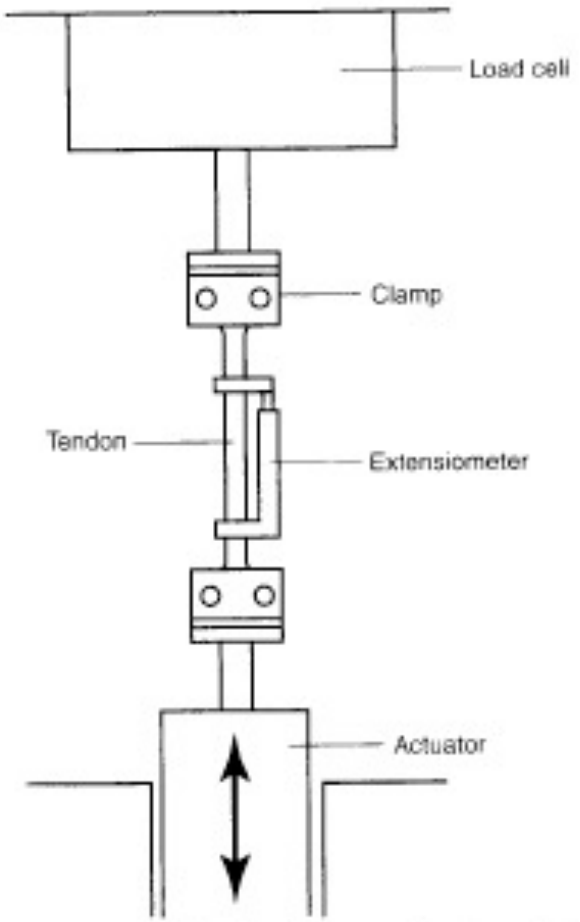
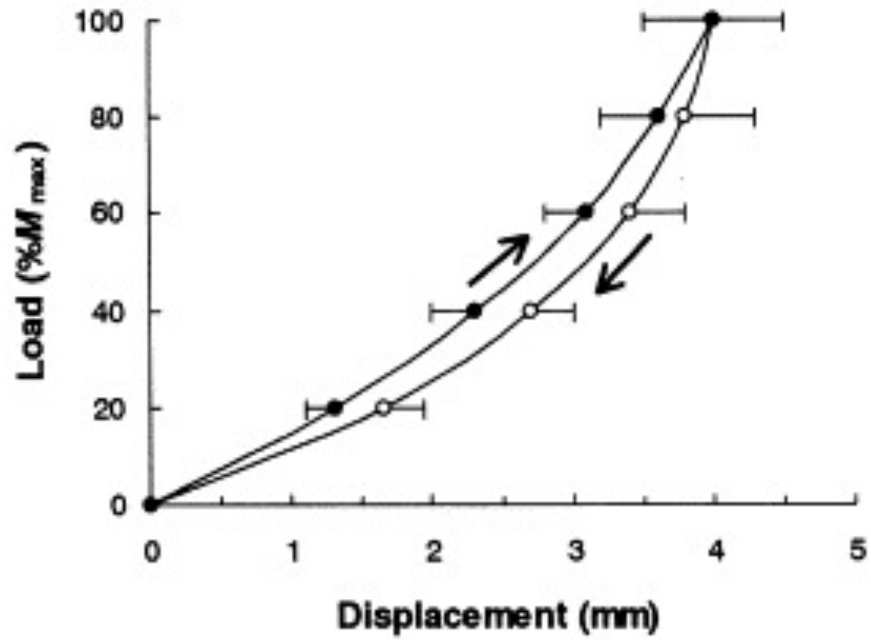
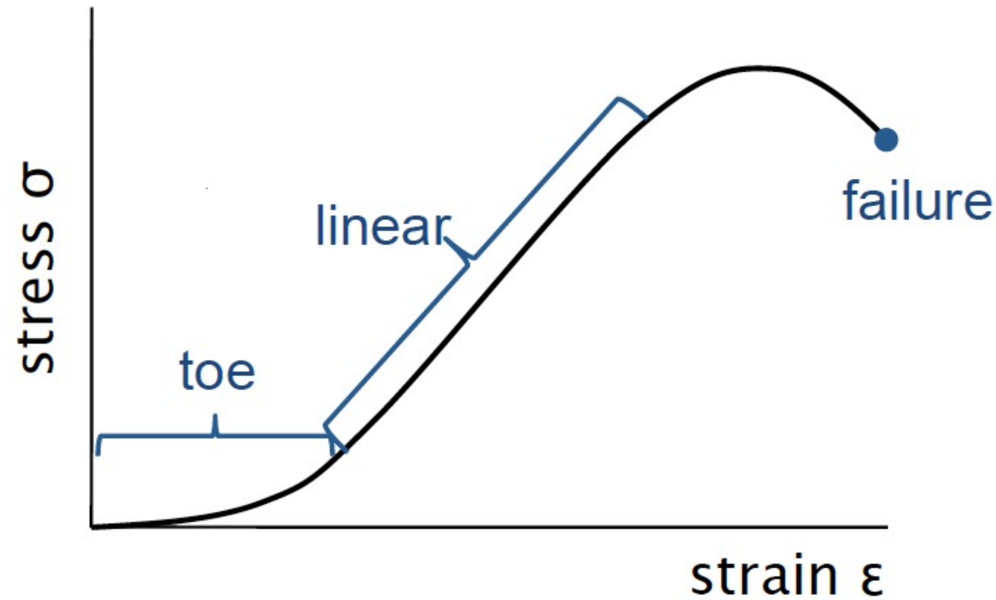


FIGURE 2-1 A testing machine that determines the stress–strain properties of a tendon. The actuator stretches the tendon. (Reprinted with permission from Alexander, R. M. (1992). *The Human Machine.* New York: Columbia University Press.)

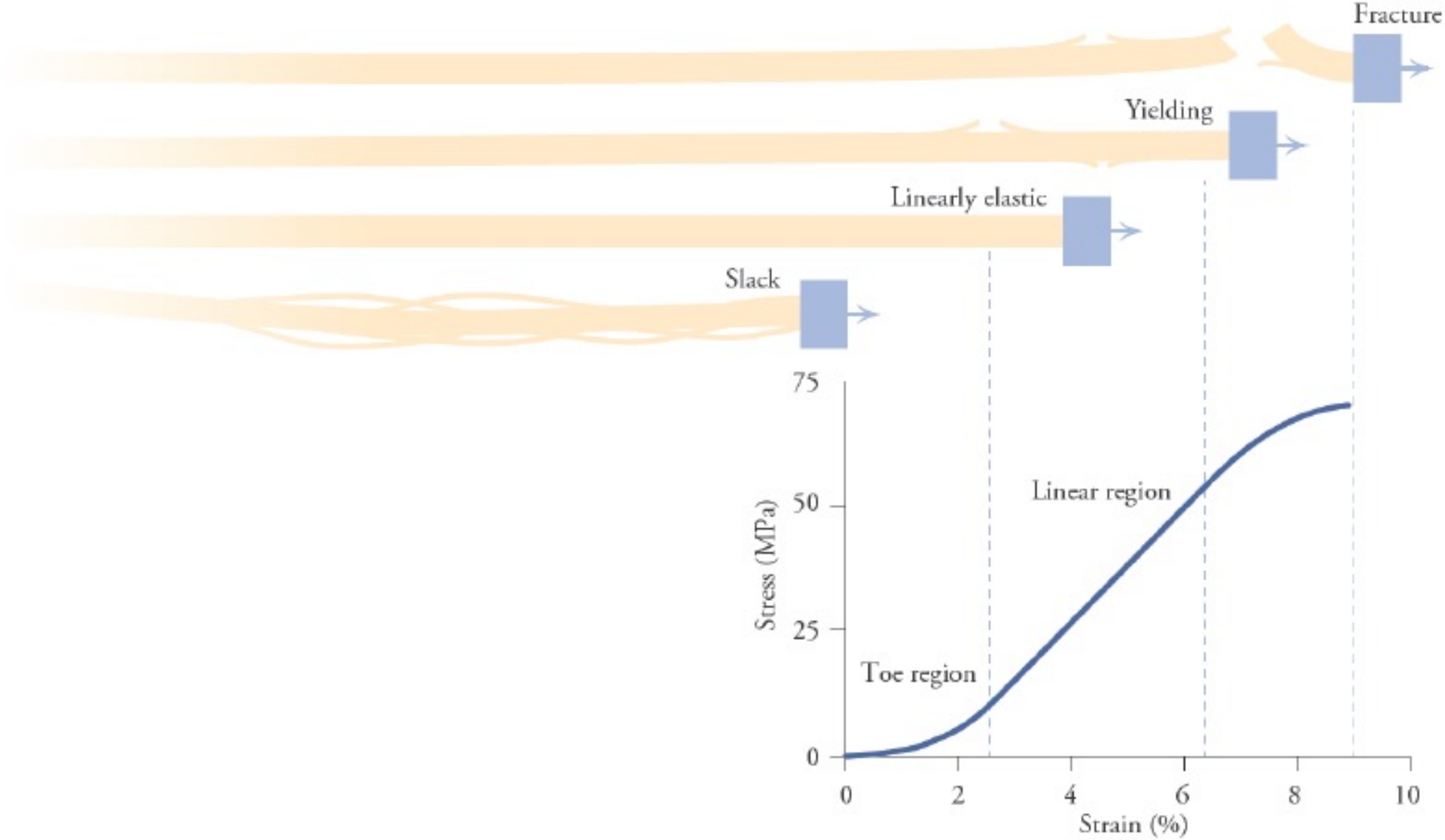


- Compliance due to “un-crimping” , collagen elasticity
- Stiffening behavior
- 93% energy return
- Typical 3% strain

Tendon stress-strain



- Low stiffness in “toe” region (differs from metals)
- Linear region (functionally most important)
- Yielding before failure (in terms of engineering stress)
- Typical values: 30MPa at 3% strain
- Other characteristics:
  - Creep
  - Stress relaxation
  - Reduced stiffness with cyclic loading


Fracture
Yielding
Linearly elastic
Slack
75
50
25
0
Stress (MPa)
Toe region
Linear region
0
2
4
6
8
10
Strain (%)

Material Properties

Material	Modulus (GPa)	Max Strain (%)	Max Stress (MPa)	Toughness (MJ/m^3)	Density (kg/m^3)	Max Energy (J/kg)
Tendon	1.5	8.0	70	2.8	1100	2500
Rubber	0.05	300	7	10.0	1200	8000
Yew wood	10	0.3	120	0.5	600	900
Spring steel	200	0.3	700	1.0	7800	130
Ancient iron	200	0.03	70	0.01	7800	1.3

Roylance, D. (2001) Stress-strain curves

5. Tendon slack length, l_s^T

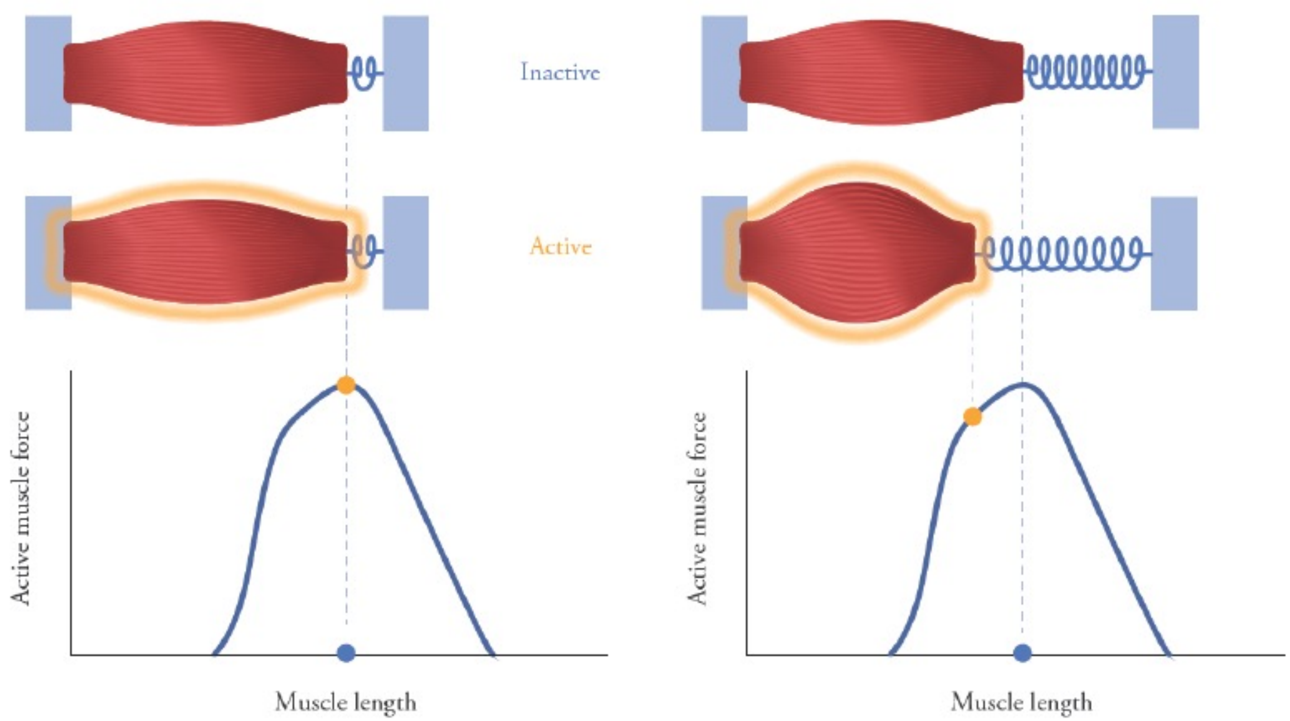
- Tendons can be modeled as nonlinear springs
- Tendon strain: $$\varepsilon^T = \frac{l^T - l_s^T}{l_s^T}$$

l_s^T is the tendon slack length, or the shortest length at which tendon develops force

Can vary from tens of centimeters to none at all

Effects on muscle force generation

- Short, rigid tendon: little length change in muscle fibers
- Long, compliant tendon: large change in muscle length and tendon is stretched. Leads to lower force, but greater range over which force can be developed.



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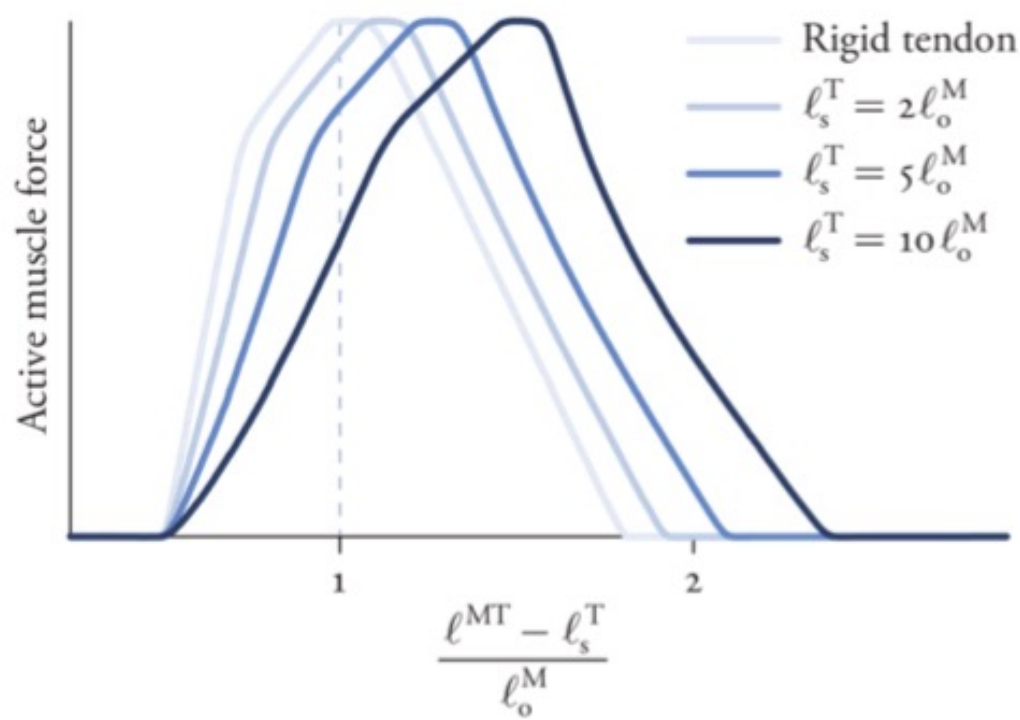

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Measuring muscle-specific parameters

Muscle-specific parameter	Symbol	Typical units
Optimal fiber length	ℓ_o^M	cm
Pennation angle at optimal fiber length	α_o	deg
Maximum isometric force	f_o^M	N
Maximum contraction velocity	v_{max}^M	ℓ_o^M / s
Tendon slack length	ℓ_s^T	cm

Muscle	Maximum isometric force (N)	Optimal fiber length (cm)	Tendon slack length (cm)	Pennation angle at ℓ_o^M (deg)
Adductor brevis	626	10.3	3.5	7
Adductor longus	917	10.8	13.2	8
Adductor magnus				
distal	597	17.7	8.7	11
ischial	597	15.6	21.6	10
middle	597	13.8	4.7	12
proximal	597	10.6	4.0	18
Biceps femoris long head	1313	9.8	32.5	10
Biceps femoris short head	557	11.0	10.6	15
Extensor digitorum longus	603	6.9	36.9	13
Extensor hallucis longus	286	7.5	32.7	11
Flexor digitorum longus	423	4.5	37.9	13
Flexor hallucis longus	908	5.3	35.4	15
Gastrocnemius lateral head	1575	5.9	37.6	12
Gastrocnemius medial head	3116	5.1	39.9	10
Gluteus maximus				
superior	984	14.7	4.9	20
middle	1406	15.7	6.8	21
inferior	948	16.7	7.0	22
Gluteus medius				
anterior	1093	7.3	5.6	18
middle	765	7.3	6.5	18
posterior	871	7.3	4.5	18
Gluteus minimus				
anterior	374	6.8	1.6	10
middle	395	5.6	2.6	0
posterior	447	3.8	5.1	1
Gracilis	281	22.8	17.2	10
Iliacus	1021	10.7	9.6	16
Peroneus brevis	521	4.5	14.8	12
Peroneus longus	1115	5.1	33.2	14
Piriformis	1030	2.6	11.5	10
Psoas	1427	11.7	10.0	12
Rectus femoris	2192	7.6	44.9	12
Sartorius	249	40.3	12.4	2
Semimembranosus	2201	6.9	34.8	15
Semitendinosus	591	19.3	24.7	14
Soleus	6195	4.4	27.7	22
Tensor fascia latae	411	9.5	45.0	3
Tibialis anterior	1227	6.8	24.1	11
Tibialis posterior	1730	3.8	28.1	13
Vastus intermedius	1697	9.9	20.2	4
Vastus lateralis	5149	9.9	22.1	15
Vastus medialis	2748	9.7	20.0	24

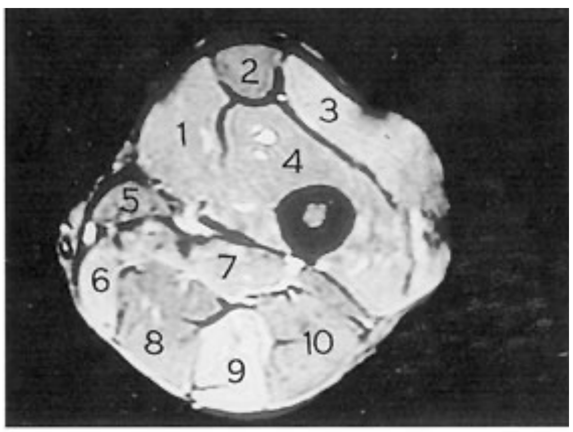
*Maximum isometric forces were derived from muscle volumes measured by Handsfield et al. (2014) in young, healthy subjects. Optimal fiber lengths and pennation angles at optimal fiber length were derived from measurements by Ward et al. (2009) in cadavers. Tendon slack lengths were derived from Rajagopal et al. (2016).

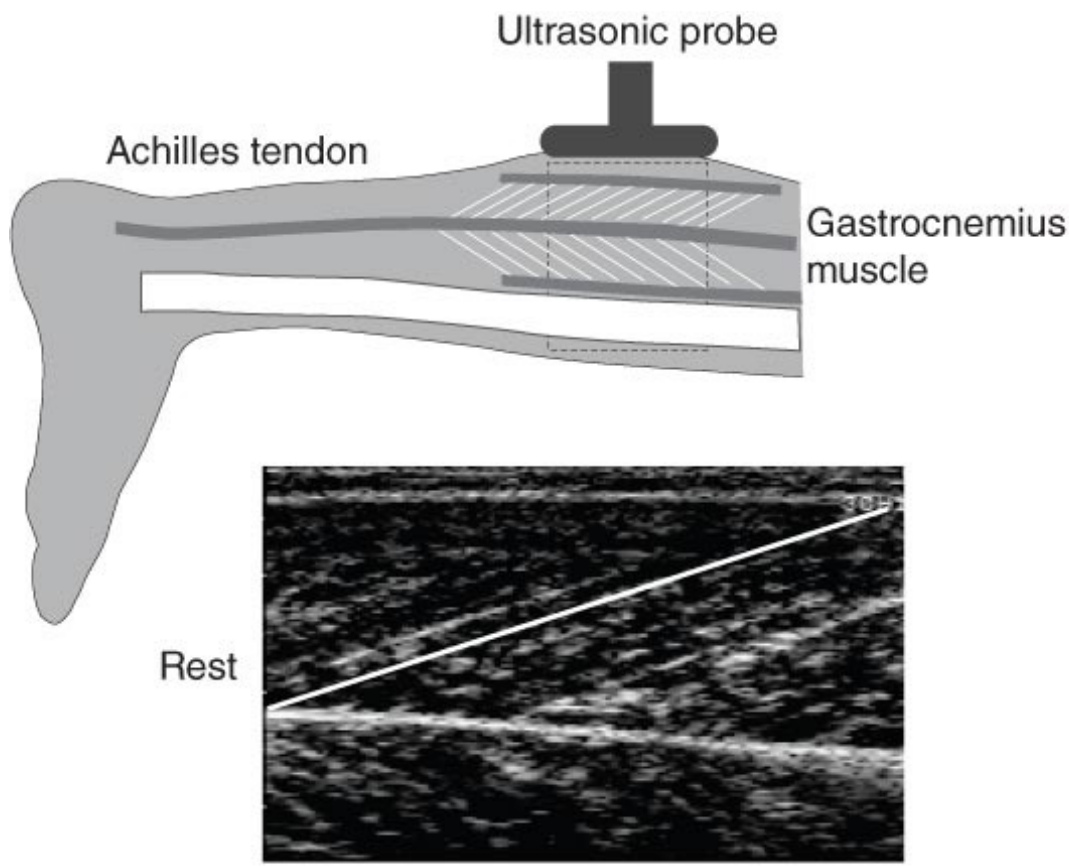
Measuring muscle-specific parameters

- Cadavers
- Subject-specific
- MRI measurements of multiple subjects

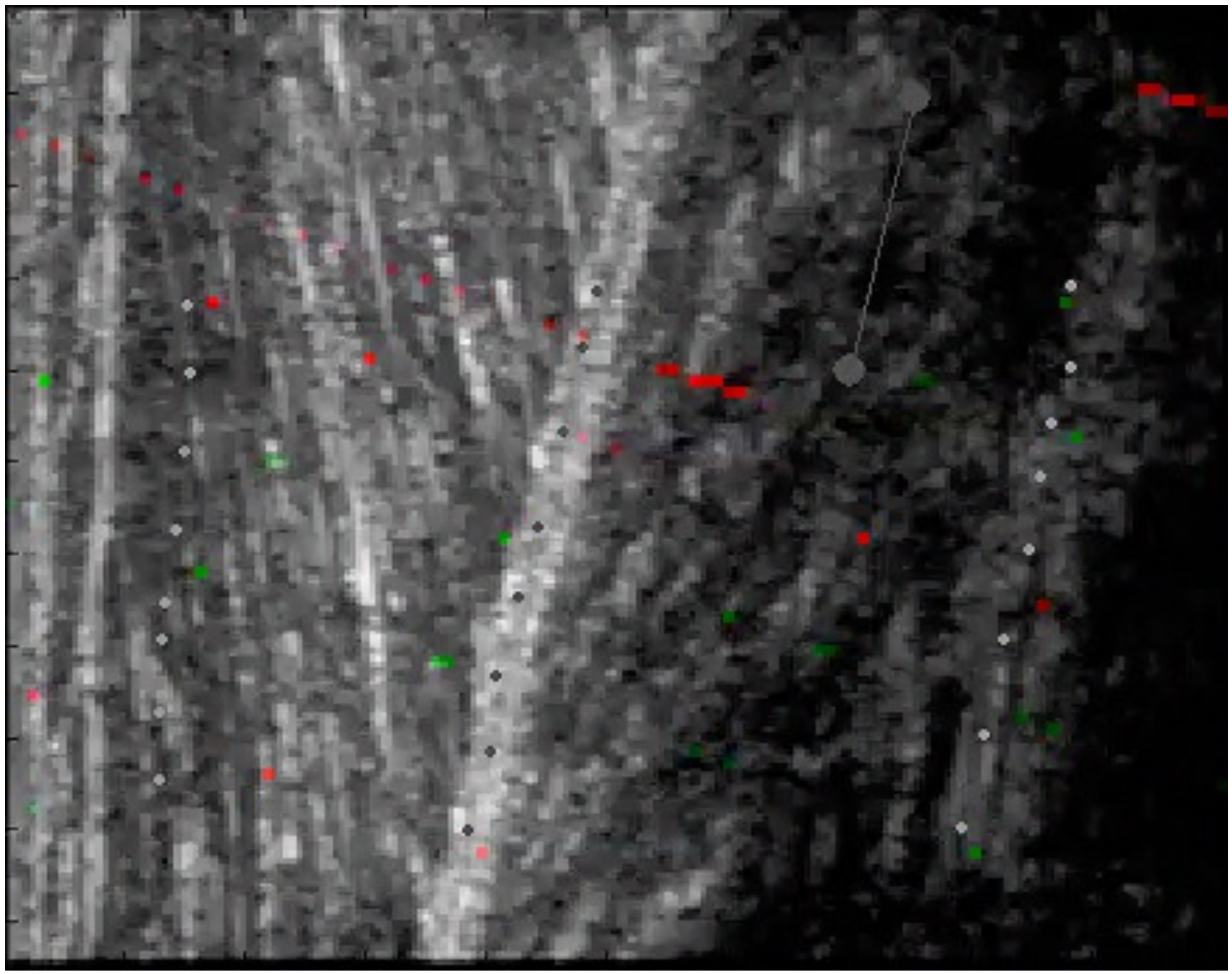
- Muscle fiber lengths and pennation angles
  - From cadavers and *in vivo* using ultrasound
- PCSA
  - Cadaver muscle mass, or muscle volume using MRI
  - $PCSA = \frac{muscle\ volume}{l_o^M}$

How do we measure PCSA?





$$PCSA = \frac{muscle\ volume}{l_o^M}$$



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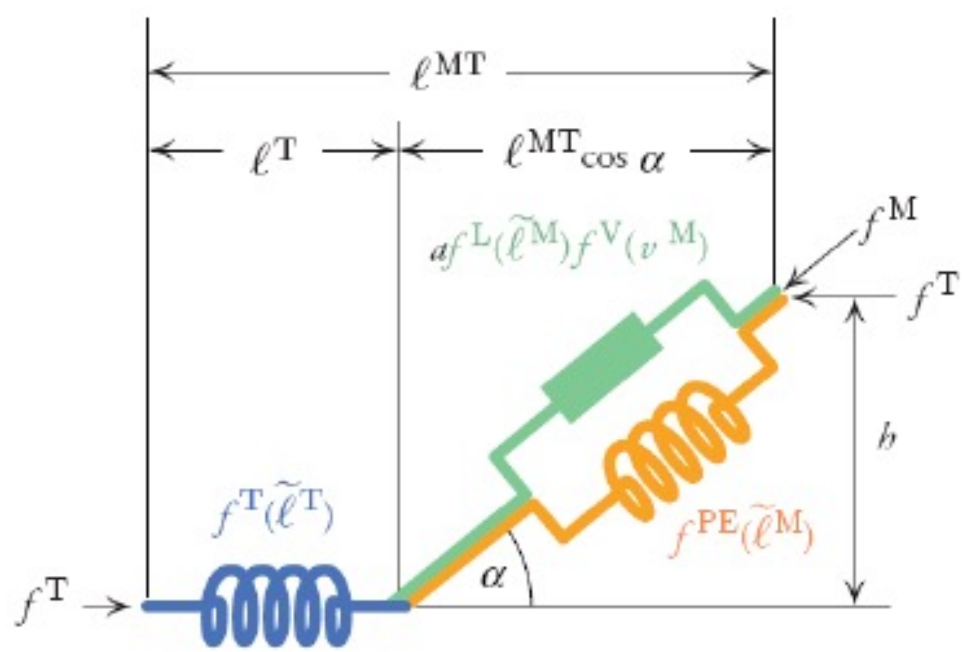
Hill-type model of musculotendon dynamics

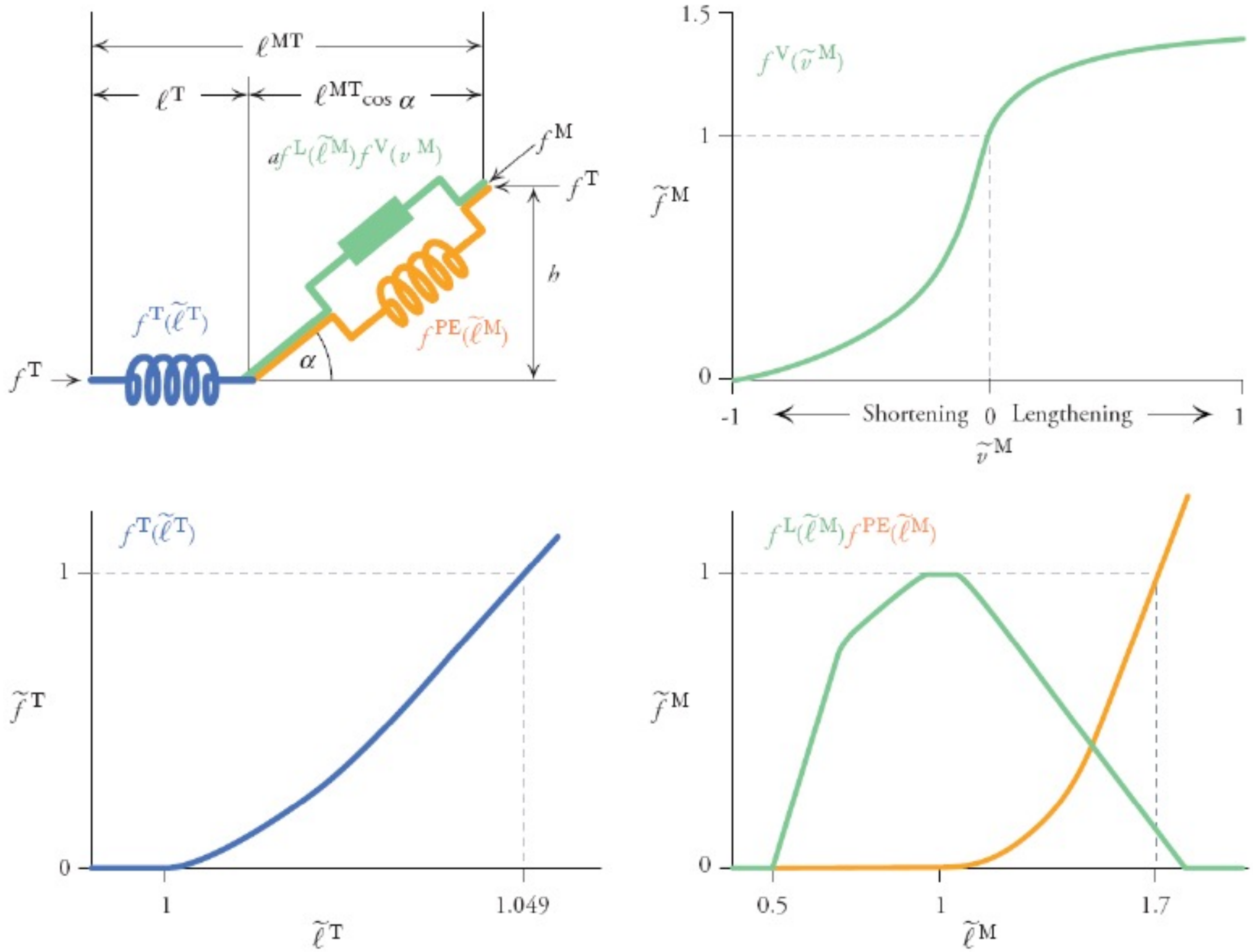
- Most widely used computational model of musculotendon dynamics
- Three components: an active contractile element, passive elastic element, and a tendon elastic element.
- Height *h* of trapezoid remains constant as muscles shorten and lengthen, thus increasing and decreasing pennation angle

$$l^{MT} = l^{M}\cos(\alpha) + l^{T}$$



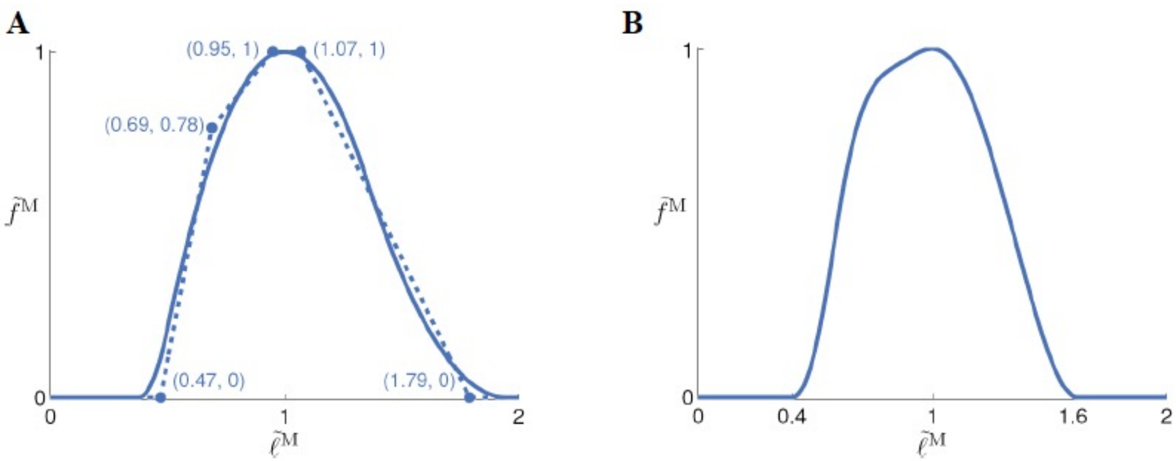
Hill-type model of musculotendon dynamics

Model element	Dimensionless curve	Symbol
Active contractile	Active force–length	$f^{L}(\tilde{\ell}^{M})$
	Force–velocity	$f^{V}(\tilde{v}^{M})$
Passive elastic	Passive force–length	$f^{PE}(\tilde{\ell}^{M})$
Tendon elastic	Tendon force–length	$f^{T}(\tilde{\ell}^{T})$



Variants of the Hill-type model

- Definitions of the four dimensionless curves
  - Tendon and Passive muscle force-length curve:
    - Quadratic in toe region and linear elsewhere
    - Approximate with a single parabolic curve or straight line
  - Active force length
    - Simple piecewise linear
    - Piecewise quadratic
    - Cubic spline



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    - Cubic spline
  - Force-velocity

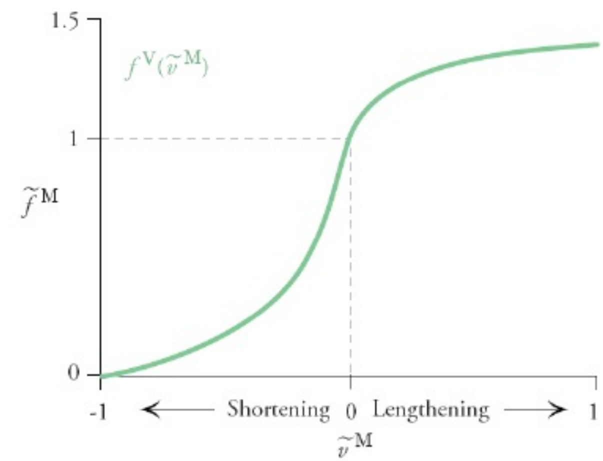
Force - Shortening Velocity

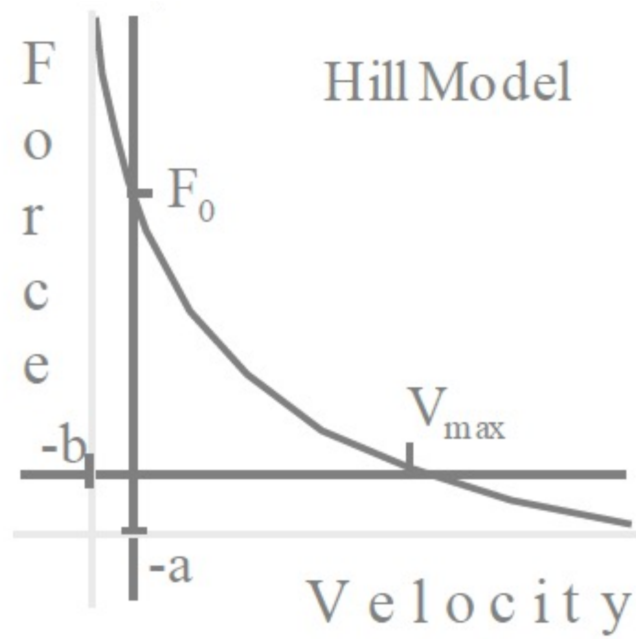
- Force-Velocity Curve (F-V)

- The Hill equation describes shortening muscle:

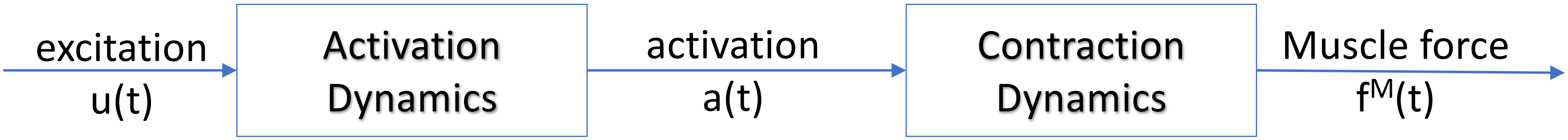
$$(\boldsymbol{F} + \boldsymbol{a})\boldsymbol{v} = \boldsymbol{b}(\boldsymbol{F_0} - \boldsymbol{F})$$

- Here, ***a*** and ***b*** are constants,
  - $\boldsymbol{F_0}$ is maximum isometric force
  - ***F*** is force
  - ***v*** is velocity





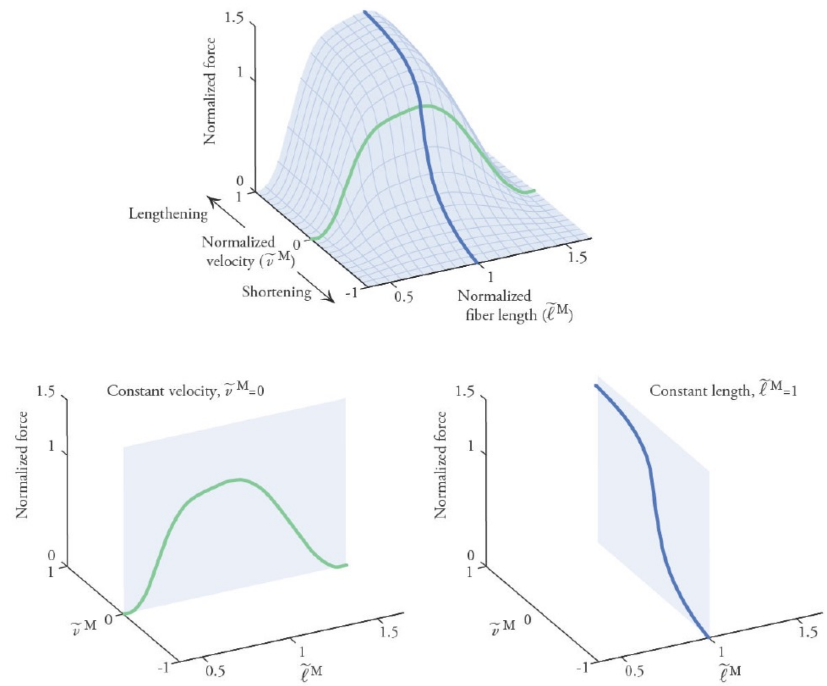
Muscle-driven simulations



Simulation:

Given: activation, length and velocity of muscle-tendon

Calculate: muscle length, velocity and force



Computing muscle force with a rigid tendon

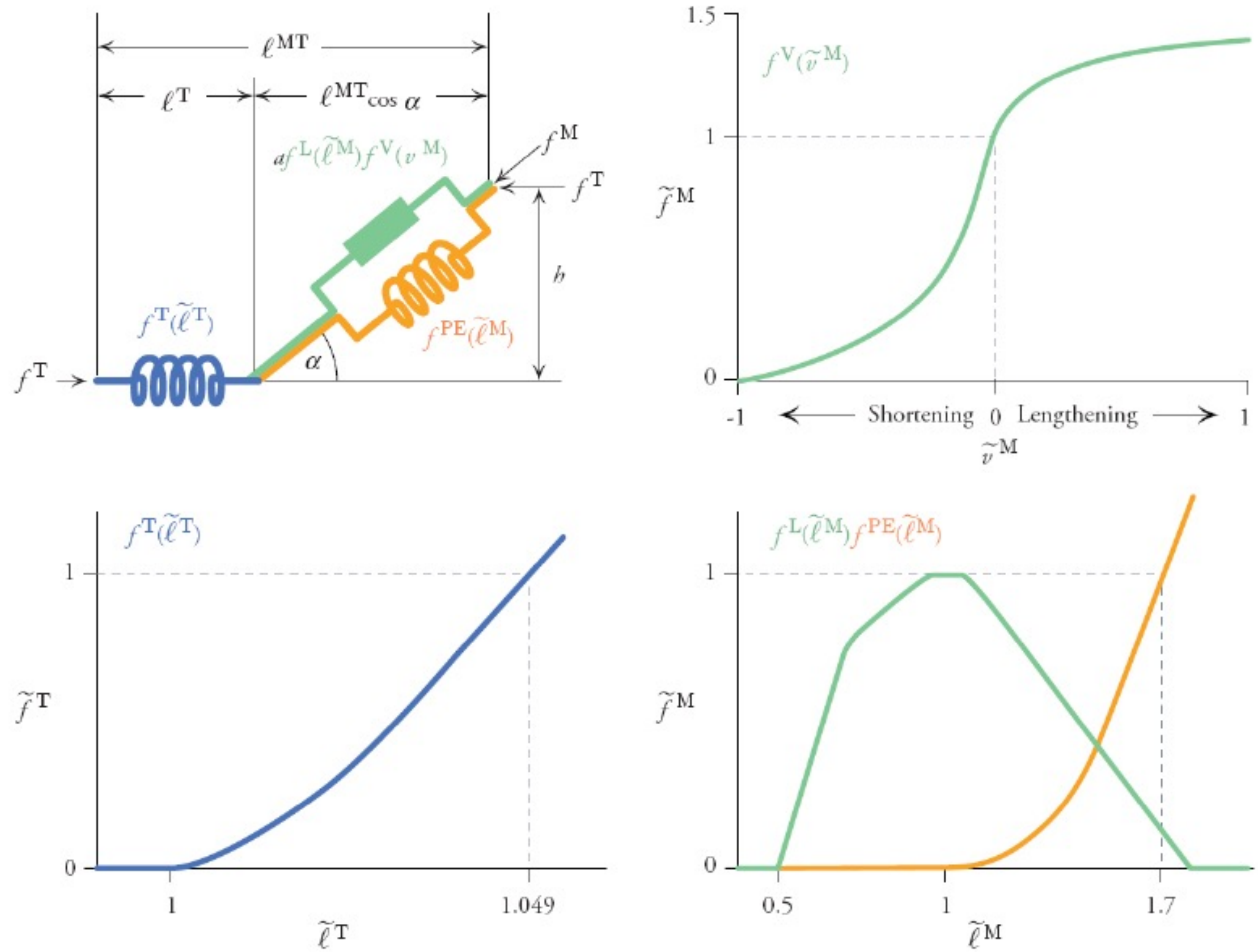
<u>Known:</u> activation, a(t); muscle-tendon length, $l^{MT}(t)$, and velocity, $v^{MT}(t)$

<u>Determine:</u> muscle force and velocity $F^{M}(t), v^{M}(t)$

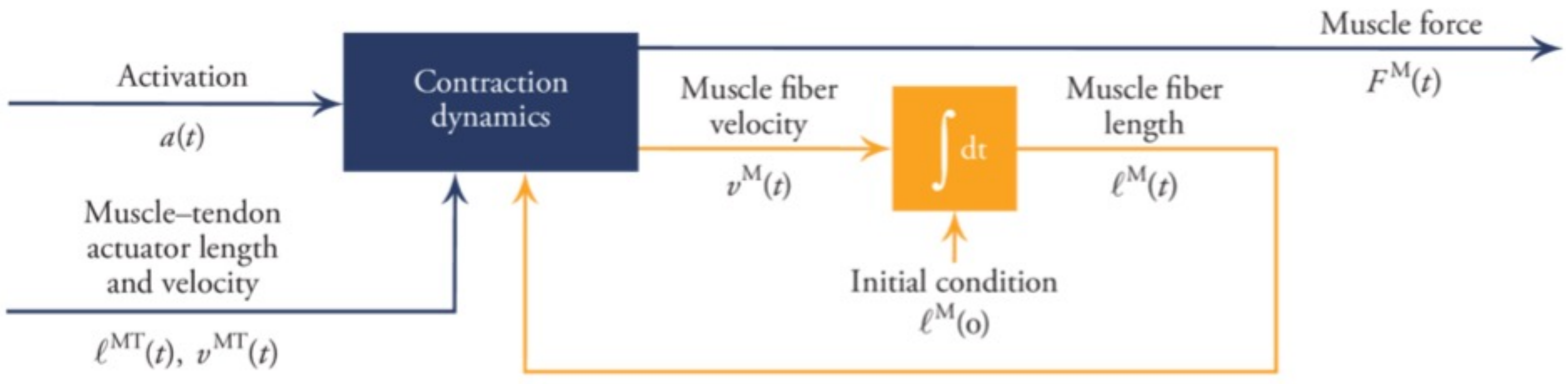
Rigid tendon: length of tendon, $l^{T}(t)$ is constant

- Step 1: $l^{M}(t) = \frac{l^{MT}(t) - l^{T}}{\cos(\phi(t))}$
- Step 2: $h = l^{M}(t)\sin(\phi(t))$
- Step3: $h = l_{o}^{M}(t)\sin(\phi_{o})$
- Step 4: $\phi(t) = \tan^{-1}\left(\frac{h}{l^{MT}(t) - l^{T}}\right)$

- $F^M(t) = F_o^M \left[a(t) f^L \left(\tilde{l}^M(t) f^V \left(\tilde{v}^M(t) \right) \right) + f^{PE} \left(\tilde{l}^M(t) \right) \right]$
- $v^{MT}(t) = -v^M(t)\cos\big(\phi(t)\big) - l^M(t)\dot{\phi}(t)\sin\big(\phi(t)\big) + v^T(t)$



Computing muscle force with a compliant tendon



- More complicated: don't know length of muscle and tendon
- Approach:
  - Start with an initial condition (muscle length and velocity) and numerically integrate to obtain muscle length at the next time step.

$$\ell^{M}(t+\Delta t) = \ell^{M}(t) - \Delta t\, v^{M}(t)$$

  - We assume that the force in the tendon and muscle are equal:

$$F^{T}(t) = F^{M}(t)\cos(\phi(t))$$

  - Calculate Tendon force from curves $F^{T}(t) = F_{o}^{M}\left[f^{T}\left(\tilde{\ell}^{T}(t)\right)\right]$
  - Calculate muscle velocity

$$\tilde{v}^{M}(t) = f_{inv}^{V}\left(\frac{f^{T}\left(\tilde{\ell}^{T}(t)\right)/\cos(\phi(t)) - f^{PE}\left(\tilde{\ell}^{M}(t)\right)}{a(t)\, f^{L}\left(\tilde{\ell}^{M}(t)\right)}\right)$$

Musculotendon Dynamics

- Muscle Fiber Architecture
  - Series/Parallel
  - Pennation angle
- Muscle Dynamics
  1. Optimal muscle fiber length
  2. Muscle fiber pennation angle
  3. Maximum isometric muscle force
  4. Maximum muscle contraction velocity
  5. Tendon slack length
- Measuring Muscle Specific Parameters
- Hill-type Muscle Model