MODELING MUSCLE PROPERTIES: BASICS

Lecture Overview

- Model Types
- Levels of Representation
- Muscle Structure
- Relevant Properties
- Force-Length Properties
- Force-Velocity Relationship
- Combined Effects
- Tendon Properties
- Passive Properties
- Muscle Fiber Types
- Muscle Moment Arms
- Activation
- Other Factors

MODEL TYPES

Reductionist – analysis aimed at simplifying a complex phenomenon into its component parts. The cross-bridge model of Huxley (1957) is a good example of this.

Phenomenological – analysis concerned only with observed phenomena, no (little) emphasis on mechanism at play. In modeling terms this means the focus is on the input and output with little concern with the events which cause the latter. (Philosophy arises from Edmund Husserl, 1859-1938).

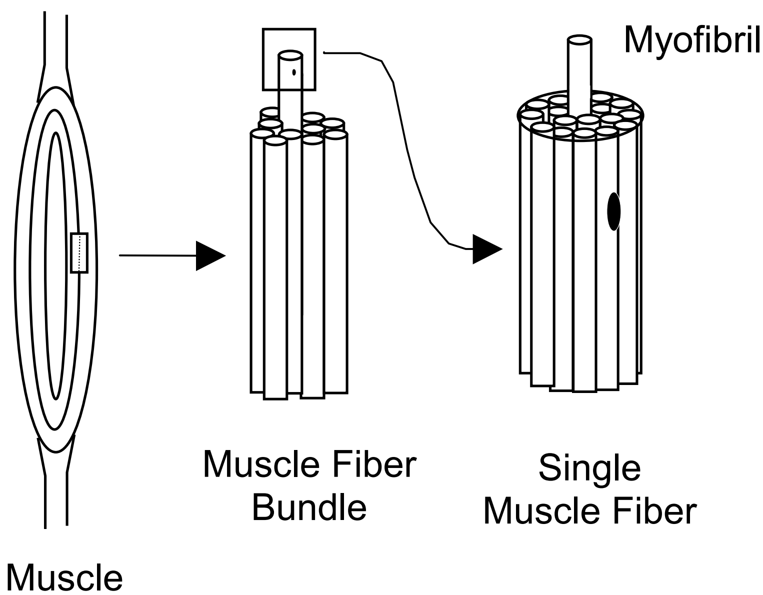
Of course division is not always clear cut.

LEVELS OF REPRESENTATION

- Individual muscle fibers
- Individual motor unit
- Individual muscles
- Selective muscle groups
- Functional groups
- Pairs of joint actuators

MUSCLE STRUCTURE

Myosin - protein forming thick part of myofibril
Actin - protein forming thin part of myofibril



At the myofibril level it is the interaction of actin and myosin which generates force. (Cross-bridges.)

The more of these proteins the higher the force which can be generated (bigger muscles produce more force).

MUSCLE STRUCTURE

Levels of organization

- Muscle
- Motor unit
- Muscle fiber
- Myofibril
- Contractile proteins actin/myosin

- Muscle fibers are grouped into motor units.

- One motoneuron will innervate a number of muscle fibers via its axonal branches. All the fibers innervated by a motoneuron constitute a motor unit.

- But which of these motor units should be selected for a given movement?

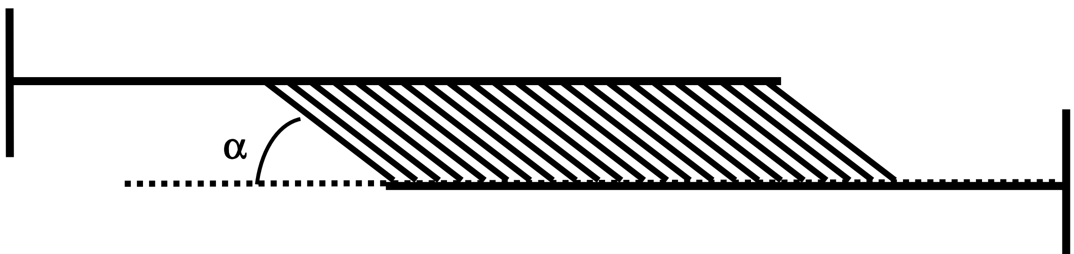
Buchthal and Schmalbruch (1980) presented the following data.

Muscle	**Biceps**	**Brachioradialis**
# Motor Units	774	330
# Muscle Fibers	580000	130000

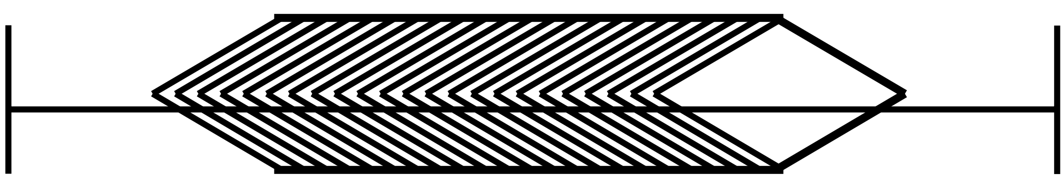
MUSCLE STRUCTURE

Fibers can be organized parallel to tendon or at an angle (α>0) to the tendon, in which case the muscle is pennated.

Unipennate



Bipennate



$$F_T = F_F \,.\, \cos(\alpha)$$

Where

F_T - force in tendon

F_F - force in muscle fiber

α - angle of pennation

MUSCLE STRUCTURE

Muscle	Pennation Angle (Degrees)
Gluteus maximus	3.4 – 5
Gluteus medius	8.0-19.0
Gluteus minimus	5.0-21.0
Biceps femoris	7.0-17.0
Gastrocnemius medialis	6.5-25.0
Gastrocnemius lateralis	8.0-16.0

$$\cos(10) = 0.98, \cos(20) = 0.94, \cos(25) = 0.91$$

MUSCLE STRUCTURE

- When activated muscle fibers develop tension which is transferred to the skeleton via the elastic structures in series with the fibers – the tendon.

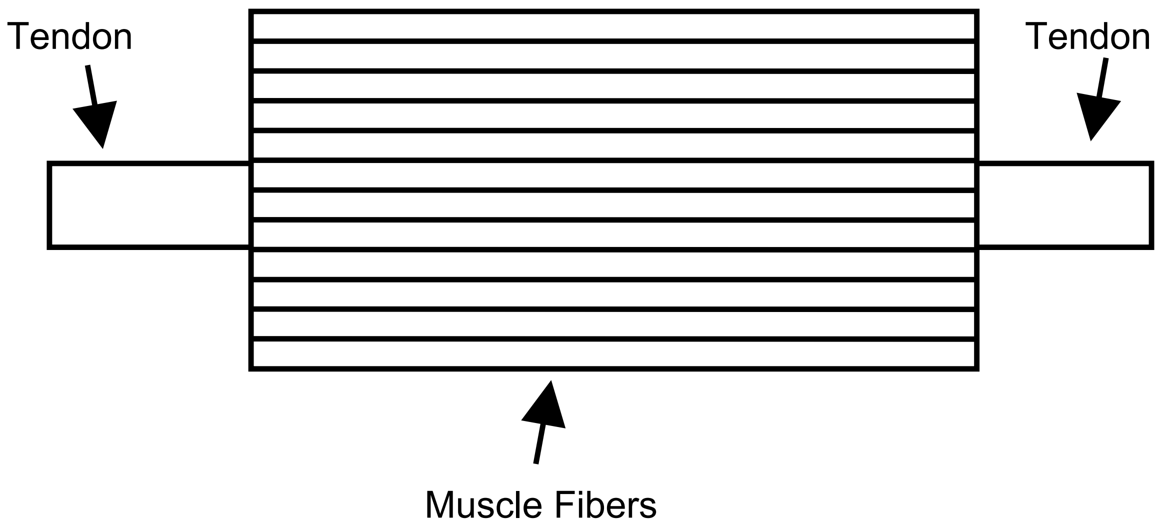
- Tendons are composed mostly of the protein collagen (~86% Harkness, 1961).

- Under a light microscope tendons have a crimped wave like appearance, the crimping (actually in the collagen) unfolds during the initial loading of the tendon.

- Tendon is not uniform along its whole length. The insertion onto the bone is a gradual transition from tendon to fibro-cartilage. The tendon is also anchored onto the bone by fibers from the periosteum of the bone (Cooper and Misol, 1970). At the other end there is a gradual transition from tendon to muscle.

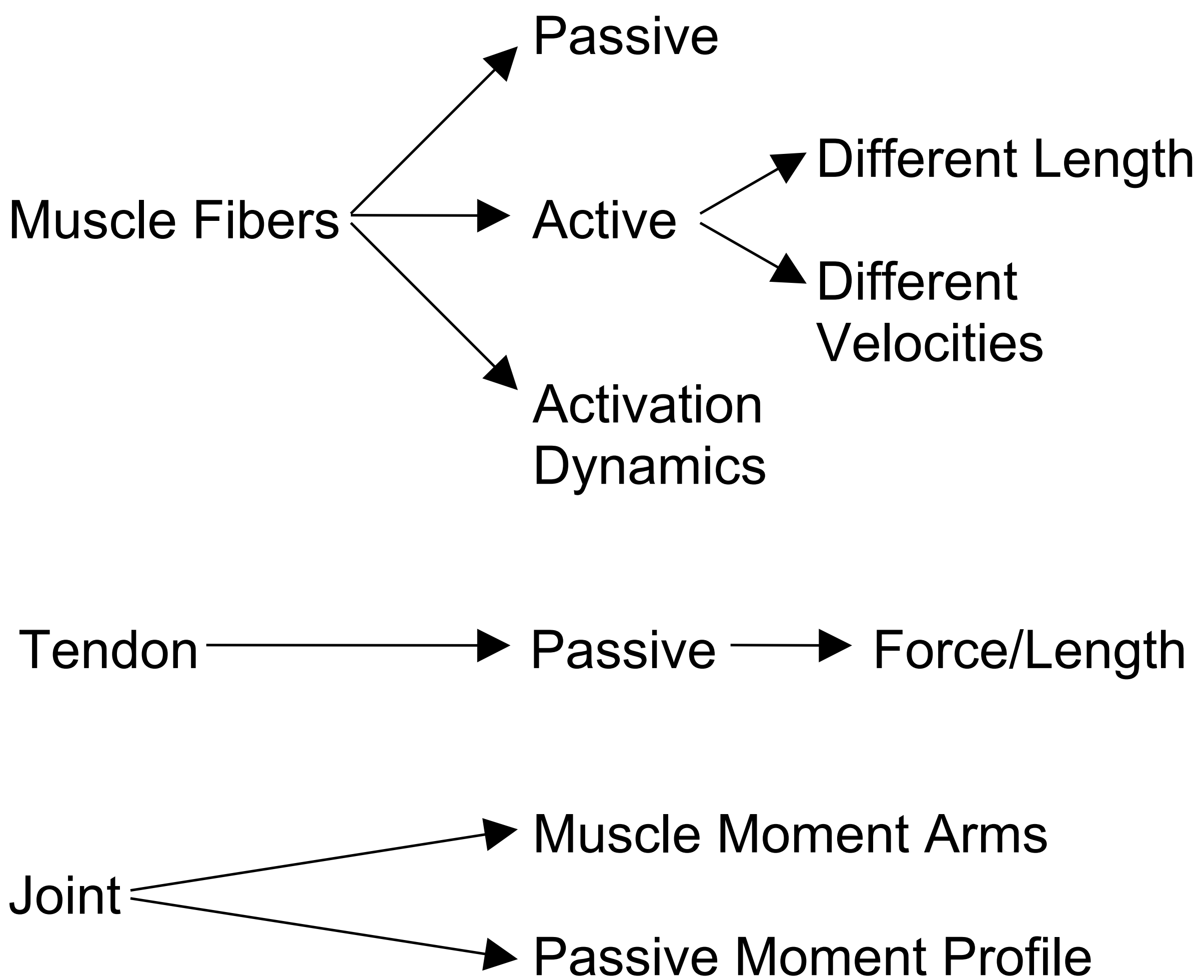
MUSCLE STRUCTURE

In biomechanics phenomenological models normally assume muscle has the following structure.



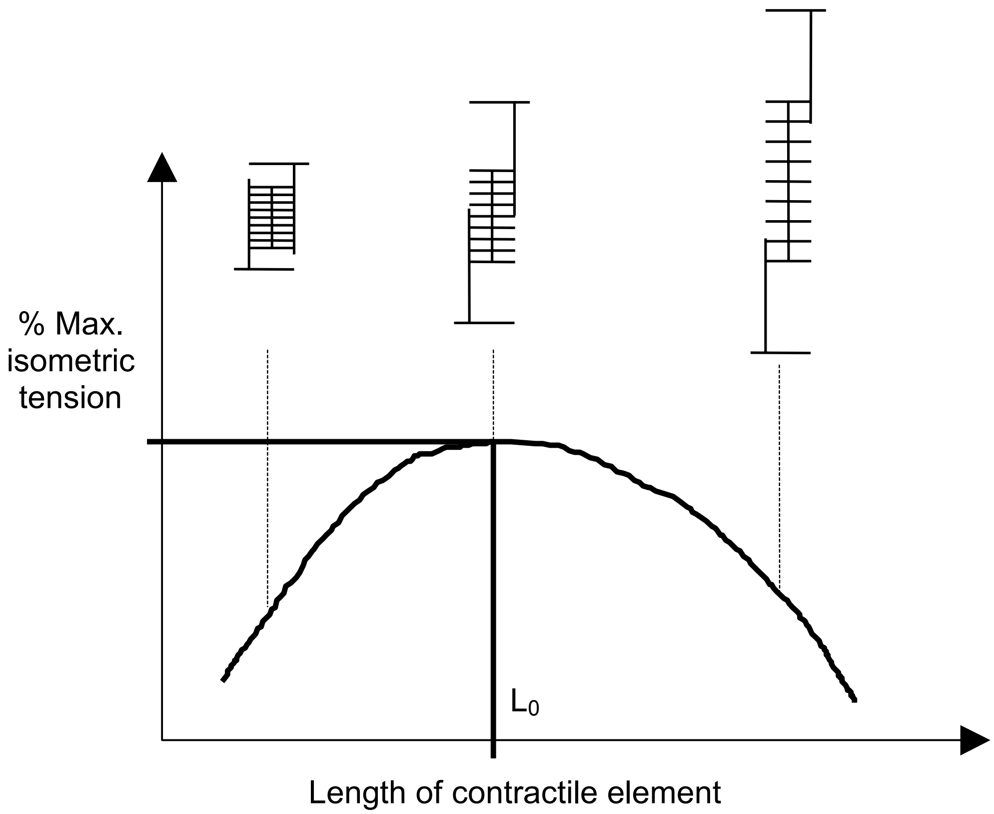
Muscle-tendon complex the assumption is that there is no transition from tendon to muscle fibers

RELEVANT PROPERTIES



FORCE-LENGTH PROPERTIES

As the length of the muscle fibers change so does the force they can produce.



Shortening - cross-bridges interfere with one another, force reduced.
Lengthening - some cross bridges are too far apart to form, so force is reduced.

*[**CF** individual fibers and whole muscle.]*

FORCE-LENGTH PROPERTIES

Simple to model the force-length relationship as it is a simple curve.

Input length of muscle fibers (L_F)

Output force produced at given length (F_I)

$$F_I = C_1 . \sin\left(\frac{L_F}{L_{FO}} - C_2 \right)$$

Constants

C_1, C_2 - are arbitrary constants, which vary with muscle.

L_{FO} - length of the muscle fiber at which the maximum force is produced, the so called optimum length.

FORCE-LENGTH PROPERTIES

The force-length relationship of muscle fibers can be modeled using the equation presented by Hatze (1981).

$$F_I = F_{IO} \cdot \exp\left[-\left(\frac{Q-1}{SK}\right)^2\right]$$

$$Q = \frac{L_F}{L_{FO}}$$

Where:-

F_I - maximum isometric tension at a given muscle fiber length

F_{IO} - maximum isometric force produced at the optimum length of the muscle fibers

L_F - length of the muscle fibers

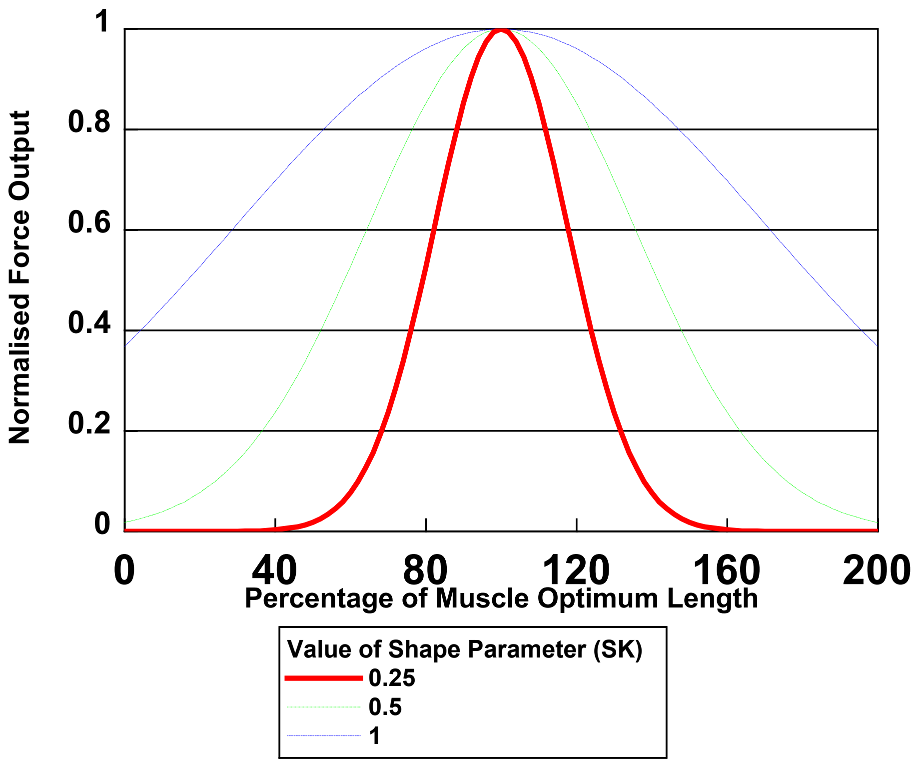
L_{FO} - length at which the muscle fibers exert their maximum tension (optimum length)

and ***SK*** is a constant specific for each muscle where ***SK*** $\geq$ 0.28.

The active range of the muscle fibers varies as the parameters SK is changed.

FORCE-LENGTH PROPERTIES

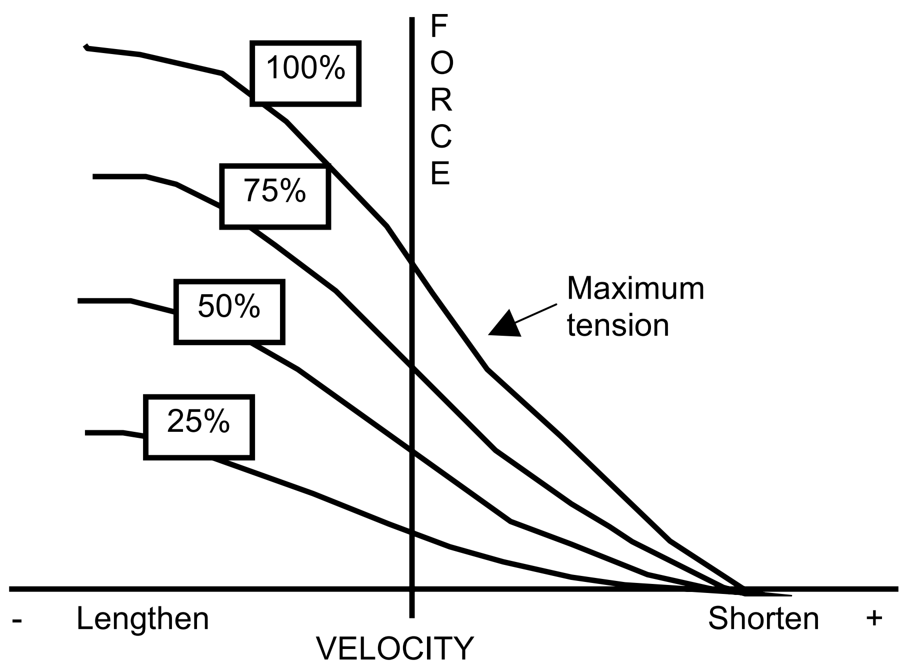
Graph showing the influence of difference values of SK, note the optimum length of the muscle fibers is assumed to be 100%.



FORCE-VELOCITY RELATIONSHIP

Concentric Muscle Action - a muscle shortening to produce force (+tive velocity). As velocity increases the force decreases as time for formation of cross-bridges is reduced.

Eccentric Muscle Action - a muscle lengthening to yield to a force (-tive velocity). As absolute velocity increases force increases. (Safety mechanism.)



FORCE-VELOCITY RELATIONSHIP

Various different relationships have been proposed to model the force velocity properties of muscle. For example

Fenn and Marsh (1935)

$$F_V = F_I . e^{-a.V_{MAX}} - b.V_F$$

Hill (1938)

$$F_V = \frac{b.(F_I + a)}{b + V_F} - a$$

Aubert (1956)

$$F_V = F_I . e^{-a.V_{MAX}} - b.L_F$$

FORCE-VELOCITY RELATIONSHIP

Hill (1938) proposed an equation for the concentric phase of the force-velocity relationship.

Input velocity of muscle fibers V_F

max. possible force at current length F_I

Output force produced F_V

$$F_V = \frac{b.(F_I + a)}{b + V_F} - a$$

Constants

a, b - are arbitrary constants, which vary with muscle and muscle fiber type distribution.

FORCE-VELOCITY RELATIONSHIP

Question: what are the values of the constants in Hill's equation?

$$a.V_{MAX} = b.F_I$$

- Faulkner, Clafin, and McCully (1986) computed the ratio of $\frac{a}{F_I}$ by fitting the data for human muscle at body temperature to Hill's equation.

  - Type I fibers the value was 0.15.
  - Type II fibers the value was 0.25.

- Faulkner et al. (1986) examining bundles of human muscle fibers found that

- Type I fibers – max. velocity of shortening of 2 $fl.s^{-1}$.
- Type II fibers – max. velocity of shortening of 6 $fl.s^{-1}$.

FORCE-VELOCITY RELATIONSHIP

When the applied load exceeds the isometric maximum (eccentric conditions) the equationof Hill does not apply (e.g. the data of Abbott et al., 1951; Katz, 1939, etc.). Mashima et al. (1972) proposed a different formulation of the equation for the eccentric phase

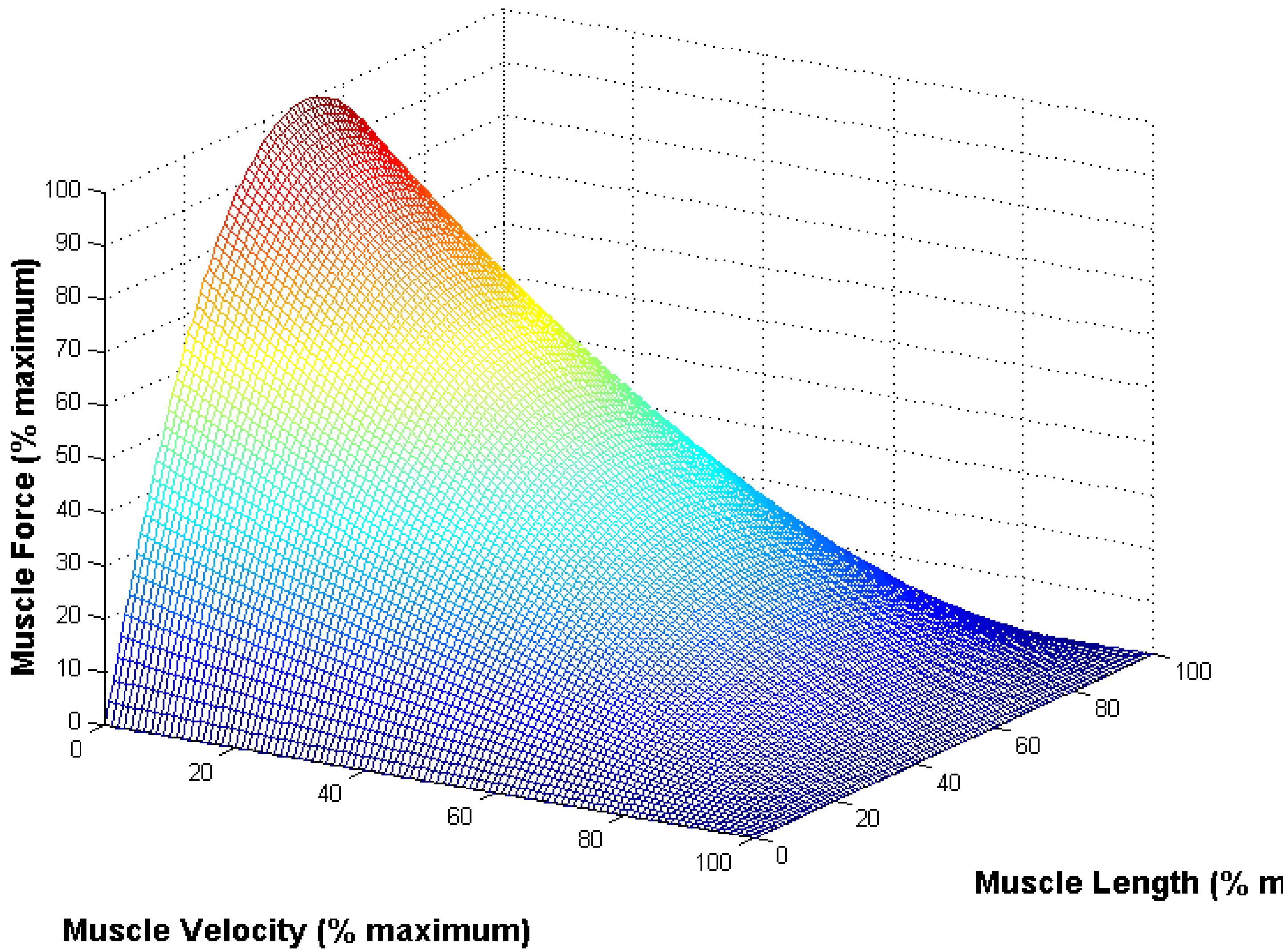
$$VV_F = \frac{b'(F_I - F)}{2.F_I - F + a'} \qquad F \rangle F_I$$

Where

$$a' = \frac{F_I}{F_{IO}} a$$

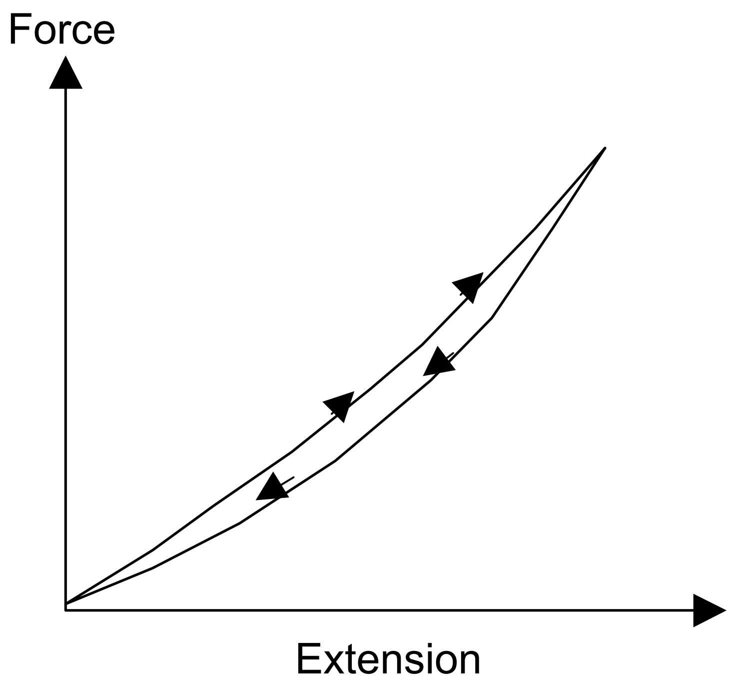
Krylow and Sandercock (1997) showed good correspondence between isolated muscle preparations and this equation.

COMBINED EFFECTS



TENDON PROPERTIES

Often assumed to be rigid, but is not, the force exerted on it by the muscle fibers will cause it to stretch.



Hysteresis - difference between the curves during loading and unloading. This is small for a tendon because it is an efficient energy store.

TENDON PROPERTIES

- Bennet, Ker, Dimery, and Alexander (1986) working with mammalian tendon found that it had a breaking strain of 0.08.

A number of models have been suggested to model tendon elasticity:-

- Hatze (1981) presented an exponential function
- Bahler (1967) used a polynomial series
- Pierrynowski and Morrison (1985a,b) and Ker, Dimery, and Alexander (1986) used Hooke's law

Although data shows that there was hysteresis in the stress-strain curve of tendon no model has yet included this. Its effect is assumed small enough to be insignificant.

TENDON PROPERTIES

If it is assumed that the curve of force applied versus amount of stretch (stress/strain) is linear, outside of toe region, Hookes law can be used to model the relationship

Input force exerted on tendon F_V

resting length of tendon $L_{T Rest}$

Output length of tendon L_T

$$L_T = L_{T Rest} + K . F_V$$

Constants

K - constant which indicates tendon compliance.

Properties

⇒Tendon tends to snap when stretched by $\approx 8\%$ of its resting length.

⇒At maximum isometric force tendon stretched by $\approx 4\%$

PASSIVE PROPERTIES
MUSCLE

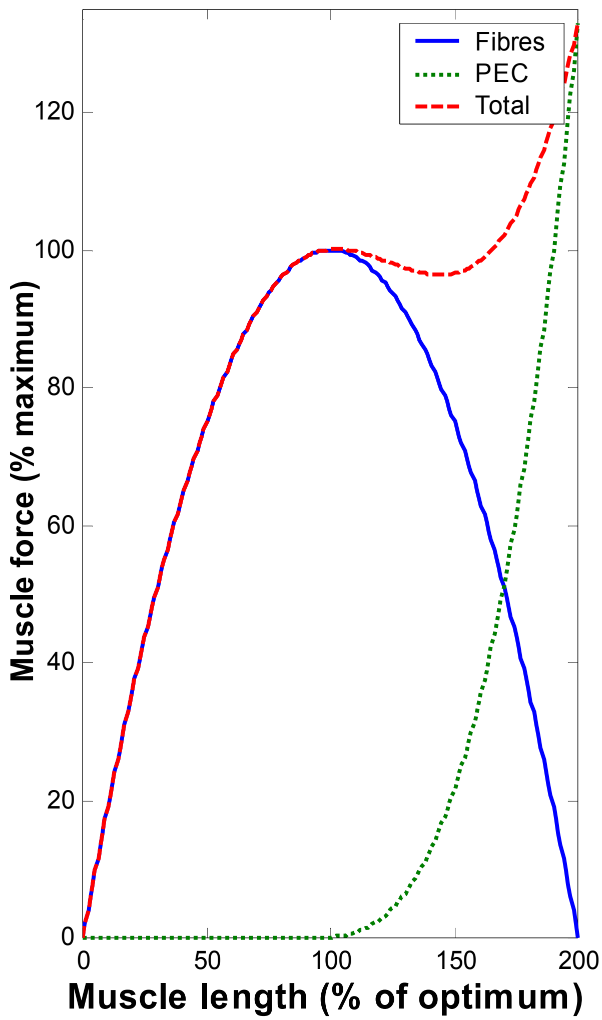
- The passive properties of muscle can be seen in isolated muscle when it is receiving no neural stimulation: as the muscle lengthens the tension developed is due entirely to those elements lying parallel to the contractile element of the muscle.

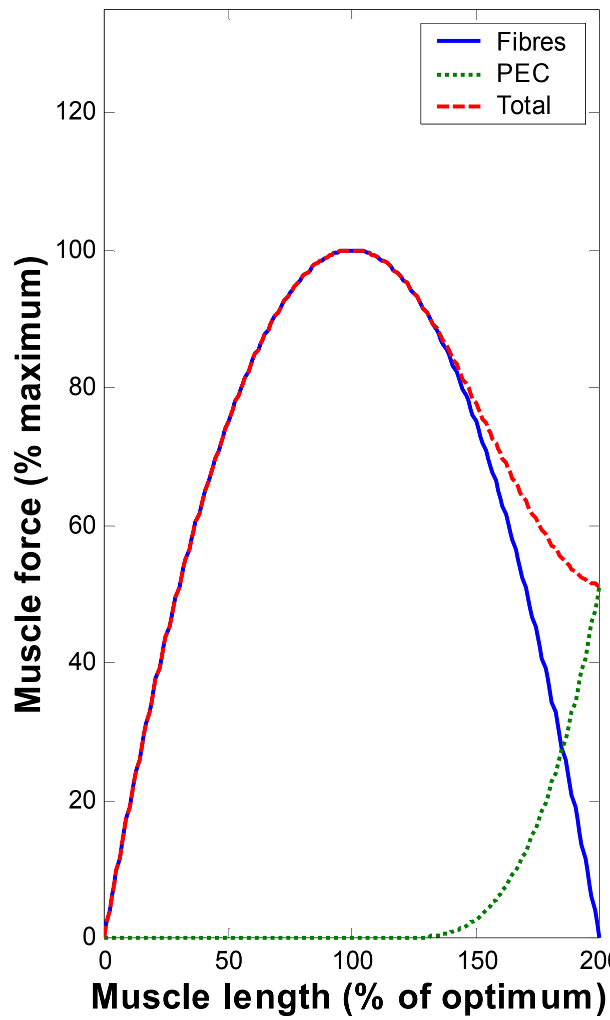
- Often called the parallel elastic element (PEC).

- Banus and Zetlin (1938) identified the site of parallel visco-elasticity as the connective tissue surrounding the muscle, the fasciae. The fasciae are the sarcolemma surrounding the individual muscle fibers, and the outer connective tissue - endomysia, and perimysia.

- Carlson and Wilkie (1974) claimed that the tension-length curve for the PEC is directly dependent on the amount of connective tissue in the muscle.

PASSIVE PROPERTIES
MUSCLE





PASSIVE PROPERTIES
MUSCLE

- Jewell and Wilkie (1958) produced a stress-strain curve for the PEC of frog skeletal muscle. This curve was very similar to those produced by Yamada (1970) for human muscle. Both curves were exponential.

Hatze (1974) and Glantz (1974) proposed the following relationship for the PEC,

$$F_{PEC} = K_1 . \left(e^{C_1 . P} - 1 \right)$$

$$P = \frac{L_{PEC} - L_{PEC,R}}{L_{PEC,R}}$$

Where

F_{PEC} - force in the parallel elastic component
K_1, C_1 - constants
L_{PEC} - length of parallel elastic component
and $L_{PEC,R}$ is the resting length of the parallel elastic component.

PASSIVE PROPERTIES
MUSCLE

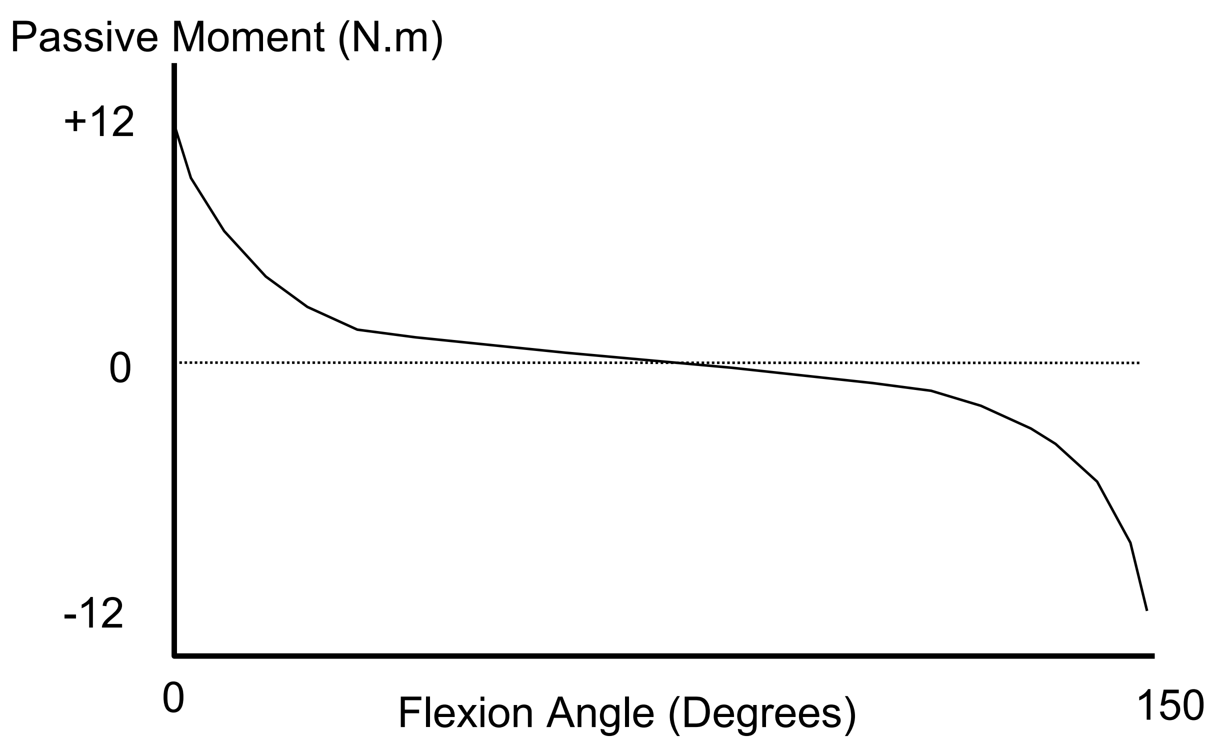
PEC is not always included in models for example

- Pierrynowski and Morrison (1985a,b) studying walking
- Bobbert et al. (1986) studying jumping
- Chapman et al., (1984) examining supination and pronation of the forearm.

In contrast Hatze (1981) examining long jumping did include the PEC.

PASSIVE PROPERTIES
JOINTS

Joint Passive Moment - is the resistance measured when a passive limb is moved. It is the net effect of all of the passive structures crossing or surrounding a joint.



The passive moment for the elbow joint

PASSIVE PROPERTIES
JOINTS

- Measurement of Joint passive visco-elasticity:-
- Quantified by the forced movement of a passive limb through a prescribed range of movement whilst measuring the resistive moments (e.g. Engin, 1979).

- There are techniques based around the passive movement of a limb at a constant velocity about a joint (e.g. Hayes and Hatze, 1977).

- Joints examined include
- Hip - example Yoon and Mansour (1982)
- Ankle - Siegler, Moskowitz, and Freedman (1984)
- Shoulder complex - Engin and Chen (1986)

- Modeling joint passive moment

$$M_P(\theta) = C_1 . e^{C_2 . \theta} + C_3 . e^{C_4 . \theta} + C_5$$

PASSIVE PROPERTIES
JOINTS

Johns and Wright (1962) examined the joint passive moment of the wrist of the cat and assessed the contributions to the moments in the mid-range of joint motion.

Joint Capsule	47 %
Muscles (passive)	41 %
Tendons	10 %
Skin	2 %

These properties can be very important, for example if the body experiences an unexpected perturbation then passive elements respond first (e.g. car crashes).

MUSCLE FIBER TYPES

Muscle fibers can be divided into two major groups: fast twitch and slow twitch. These fiber types have different histochemical and biochemical profiles.

- Type I fibers have a long contraction time (slow twitch), are well adapted for aerobic glycolysis.

- Type II fibers have short contraction times (fast twitch).
  - Type IIa fibers have a high capacity for anaerobic metabolism but also have a capacity for aerobic metabolism.
  - Type IIb fibers also have a high capacity for anaerobic glycolysis and some limited capacity for aerobic metabolism.

MUSCLE FIBER TYPES

Determination of muscle fiber type.

- Extrapolate from cadaver data, e.g. Johnson et al. (1973).

- Biopsy the subject.

Problems

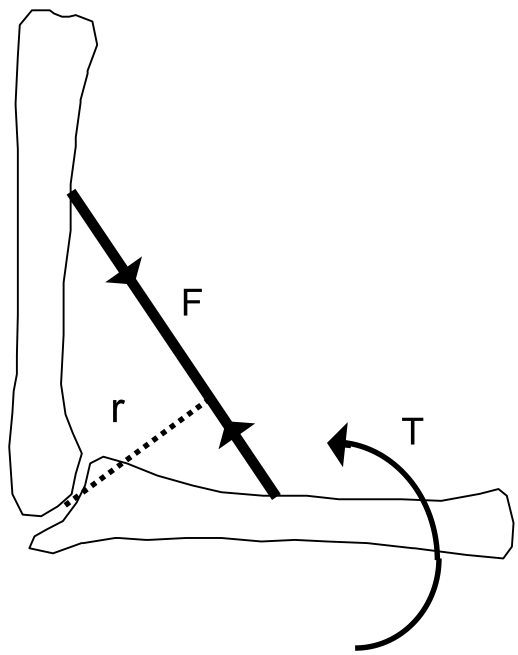
- Fiber type distributions vary between individuals.

- For example Lexell et al. (1983) have shown that there is regionalization in the distribution of muscle fiber types, so that one fiber type predominates towards the center of the limb. These limitations mean that accurate biopsy data is difficult to obtain.

- Blomstran and Ekblom (1982) in a methodological examination of the estimation of muscle fiber distribution using the muscle biopsy technique, have shown that at least two samples are required to reduce the variability of the muscle fiber type distribution estimation.

MUSCLE MOMENT ARMS

Moment produced by a given muscle is a function of the muscle force and the moment arm of the muscle.



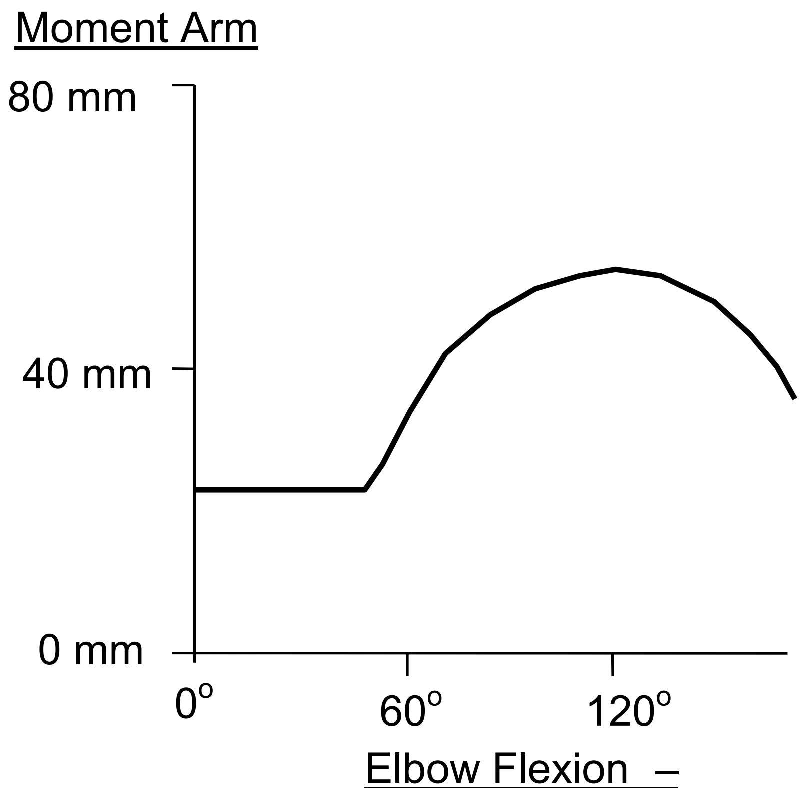
moment = moment arm of force x force

$$T = r.F$$

The moment arms of muscles (r), vary with the joint angle.

MUSCLE MOMENT ARMS

For example the graph shows how the moment arms the elbow flexors change with joint angle.



Biceps

MUSCLE MOMENT ARMS

Moment arm data can be obtained from

- Cadaver dissection
- In vivo using a medical imaging technique

To generalize such data a function is often fitted to it, so that the moment arm of a muscle can be expressed as a function of joint angle. For example Voigt et al.(1995) presented the following equation for the moment arm of the Achilles tendon.

$$r = a + b.\theta + c.\theta^2 + d.\theta^3$$

Where

r - moment arm
θ - joint angles
a - constant (-5.03442 x 10^{-1})
b - constant (1.10511)
c - constant (-4.78432 x 10^{-3})
d - constant (-2.00026 x 10^{-7})

ACTIVATION

The force a muscle produces is modulated in two ways:-

- recruit more motor units (**recruitment**)
- increase the rate of discharge of the already active motor units (**rate coding**)

What is the order of recruitment?

Henneman size principle (Henneman et al., 1965)

- Slow Twitch
- Fast Twitch Fatigue Resistant
- Fast Twitch Fatigable

What are relative contributions?

Milner-Brown et al., (1973) examining the first dorsal interosseous found that up to 33 percent of MVCF was due to the recruitment of more fibers rather than from increased force output from the already recruited fibers.

“Increased rate proved to be responsible for the coarser adjustments that are made at higher force levels.”
(page 384, Milner-Brown et al.,1973)

ACTIVATION

Active State – Sandow et al. (1965) introduced the concept that the active state should be related to the number of calcium ions bound to the troponin.

"...we define the active state q to be the relative amount of Ca bound to troponin."
(page 139, Ebashi and Endo, 1968).

When q=0 there are no calcium ions bound to the troponin, or at least it is at its resting level, so the muscle is inactive. When q=1 the troponin is saturated with calcium ions, so the muscle is maximally active. Therefore for a given length and velocity the force developed by a contractile element is a function of q.

ACTIVATION
MODELS OF ACTIVATION DYNAMICS

- Active state and degree of activation are often used synonymously.

- Rate coding and recruitment are generally ignored (certainly for whole muscle simulations), and reference is made to the muscle degree of activation or active state.

- Some would argue it is not a direct relationship between a muscles forces and its active state.

- Muscle force depends on (using term activation)
  - current level of activation which depends on
    - previous level of activation
    - level of stimulation.

ACTIVATION
MODELS OF ACTIVATION DYNAMICS

Pierrynowski and Morrison (1985) presented equations that allowed the next level of active state of a muscle to be determined given the previous state and allowing for either maximum stimulation or no stimulation. The equations were:-

For full stimulation

$$q(t) = q(t - \Delta t) + \left(1 - e^{-\Delta t / C_1}\right).(1 - q(t - \Delta t))$$

For full relaxation

$$q(t) = q(t - \Delta t) - \left(1 - e^{-\Delta t / C_2}\right).(1 - q(t - \Delta t))$$

Where

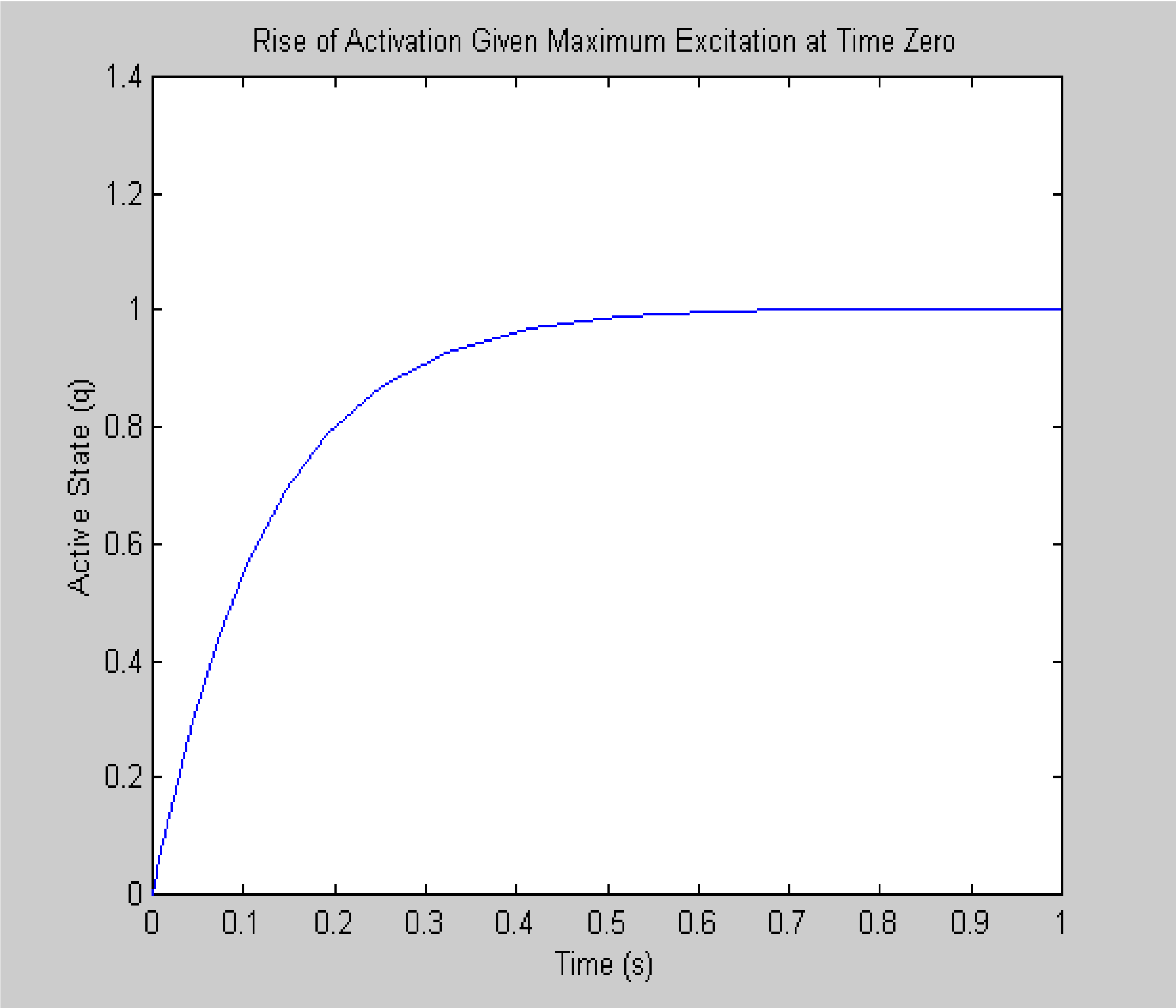
$q(t)$ - active state at time t

Δt - time interval

and C_1, C_2 are time constants

ACTIVATION

MODELS OF ACTIVATION DYNAMICS



ACTIVATION
MODELS OF ACTIVATION DYNAMICS

Another model is based around the following differential equation (Zajac, 1989),

$$\frac{dq}{dt} = (u - q) + (K_1 . u + K_2)$$

Where

u - neural excitation $(0 \le u \le 1)$
and K_1, K_2 are time constanst

Or assume activation is bang-bang.

ACTIVATION
MODELS OF ACTIVATION DYNAMICS

What are the time delays?

Muscle	Contraction Time (ms)	%Type I Fibers
Soleus	120	80
Lateral Gastrocnemius	118	49
Biceps Brachii	66	40
Vastus Lateralis	66	46

These time delays can be significant for certain movements.

DATA SOURCES

A lot of the model parameters are determined from in vitro specimens (e.g. force-length properties) or from cadavers (e.g. muscle moment arm data).

How representative are these data of what occurs in vivo?

Can these model parameters be determined in vivo?

REVIEW QUESTIONS

1) Describe the basic structure of muscle?

2) What is the force-length relationship of the muscle fibers? What is this caused by?

3) What is the force-velocity relationship of muscle? What happens during the eccentric phase? Based on whose work is the equation commonly used to describe the concentric phase of the force-velocity relationship?

4) What are key properties of tendon?

5) What are the sources of the passive moment at human joints? How might this passive moment be of use?

6) What are the implications of the moment arms of muscles varying with joint angle?