ELEC ENG 795:

Quantitative Electrophysiology

Notes for Lecture #5

Wednesday, October 11, 2006

3.2 Muscle biomechanics

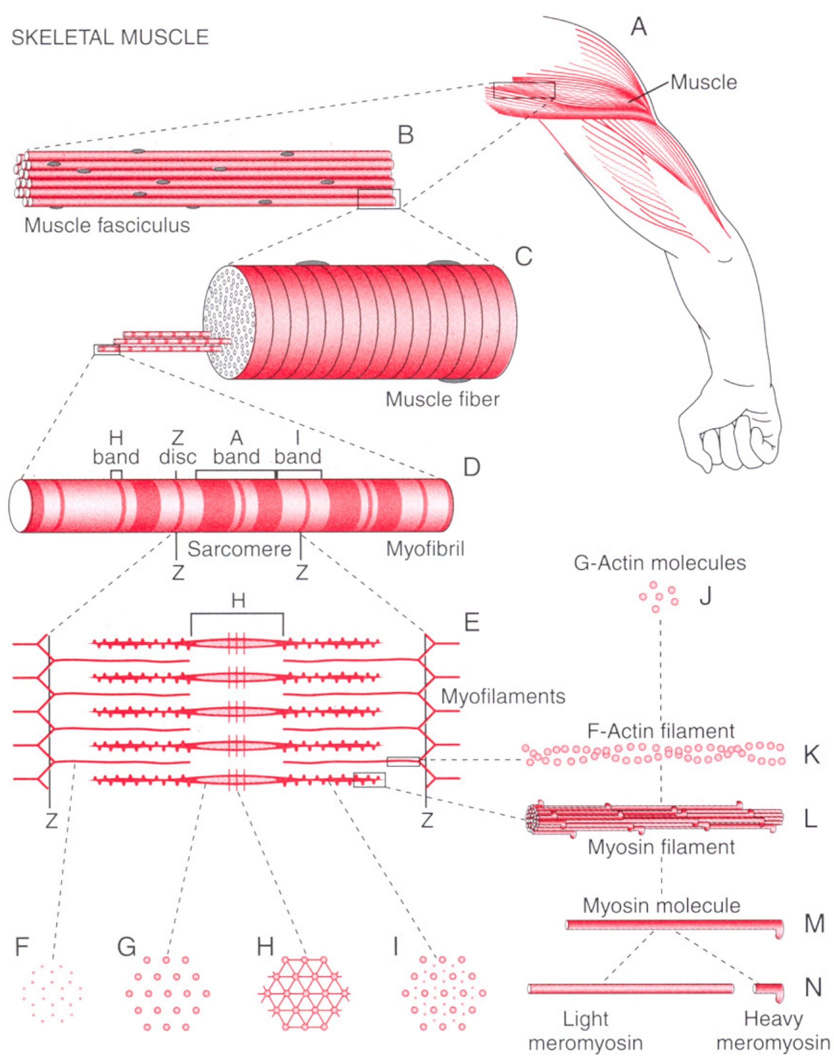


FIGURE 6 – 1

Organization of skeletal muscle, from the gross to the molecular level. *F, G, H,* and *I* are cross sections at the levels indicated. (Drawing by Sylvia Colard Keene. Modified from Fawcett DW: Bloom and Fawcett: A Textbook of Histology. Philadelphia: WB Saunders Co, 1986.)

Organization:

- skeletal muscle is made up of *muscle fibers*
- each fiber is a single cell
- the contraction of a fiber is achieved by the *motor proteins actin & myosin*

(from Guyton and Hall, 10^{th} Edition)

Fiber orientation:

– muscles that undergo large length changes or high velocities usually have long fibers running lengthwise e.g. biceps brachii

(a)
(b)

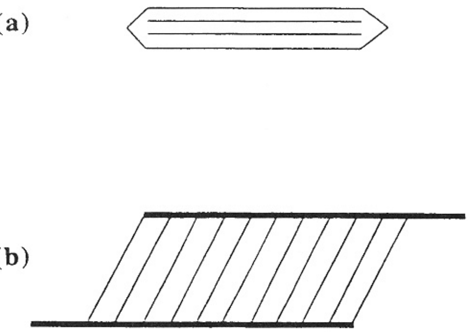
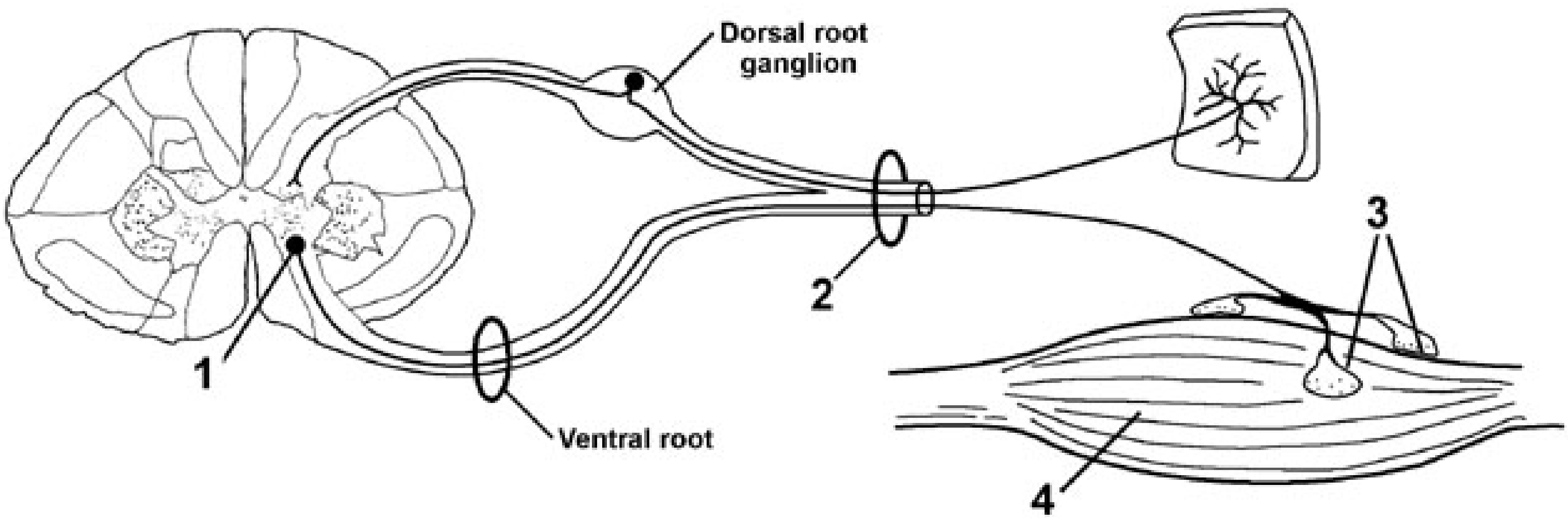


Fig. 10.14 Two common arrangements of fibers within a muscle. In the fusiform arrangement (a), fibers run the length of the muscle. The pennate structure (b) has fibers attached to tendon (bold) at an angle, like the pinna of a feather to its shaft.

– muscles that undergo only small length changes but are required to produce large forces or stiffness have fibers arranged at an angle to the tendons to which they are attached e.g. flexor carpi radialis

Muscle fiber innervation:

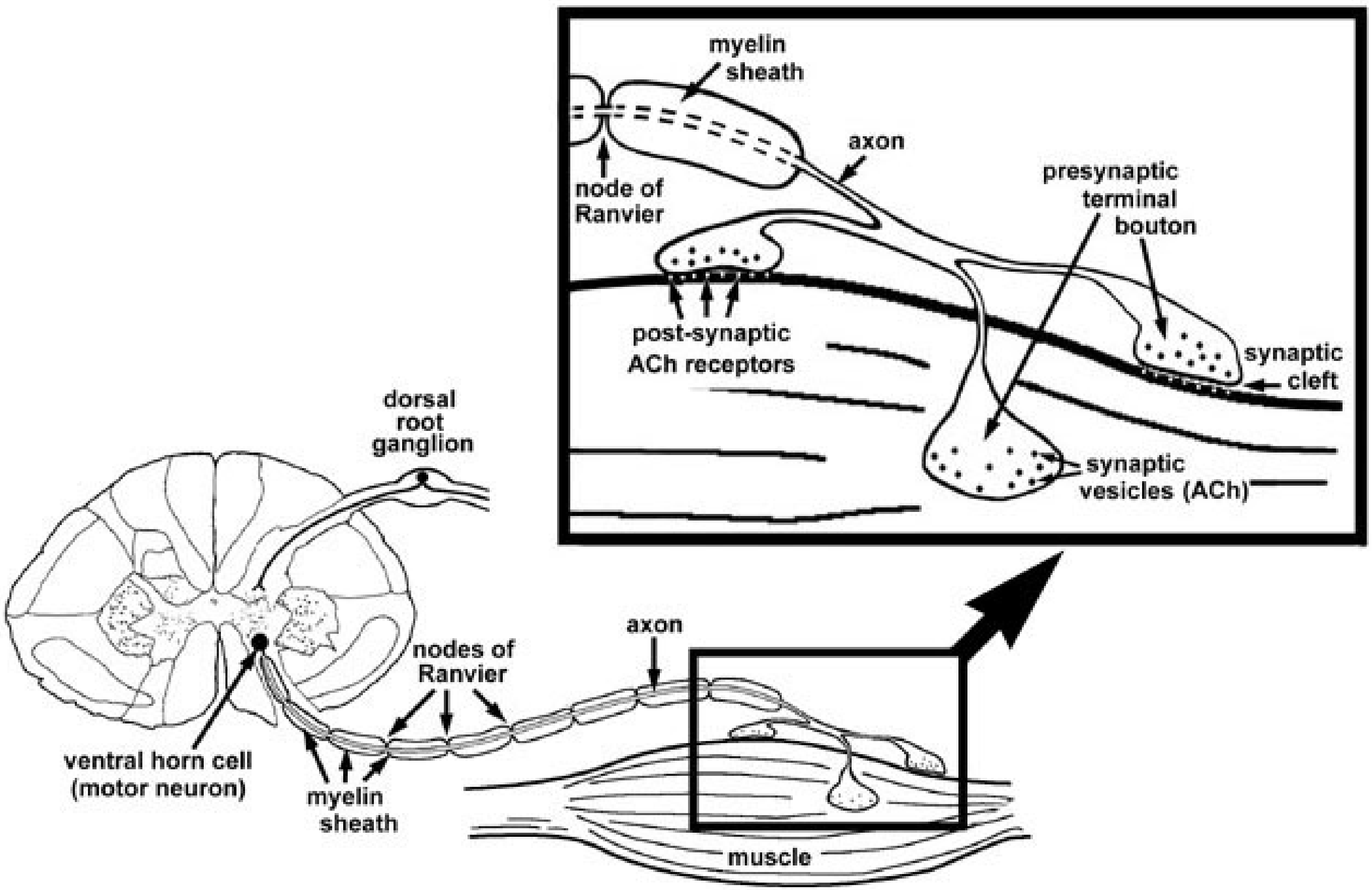


1. Motor neuron
2. Peripheral nerve
3. Neuromuscular junction
4. Muscle

Motor unit:

A *motor unit* is defined as an individual motor neuron plus all the muscle fibers that are innervated by that neuron.

Neuromuscular junction:



Structure of the neuromuscular junction (cont.):

The nerve terminal contacts the muscle fiber at an *end plate*.

The pre- and post-synaptic membranes form a specialized “gutter”.

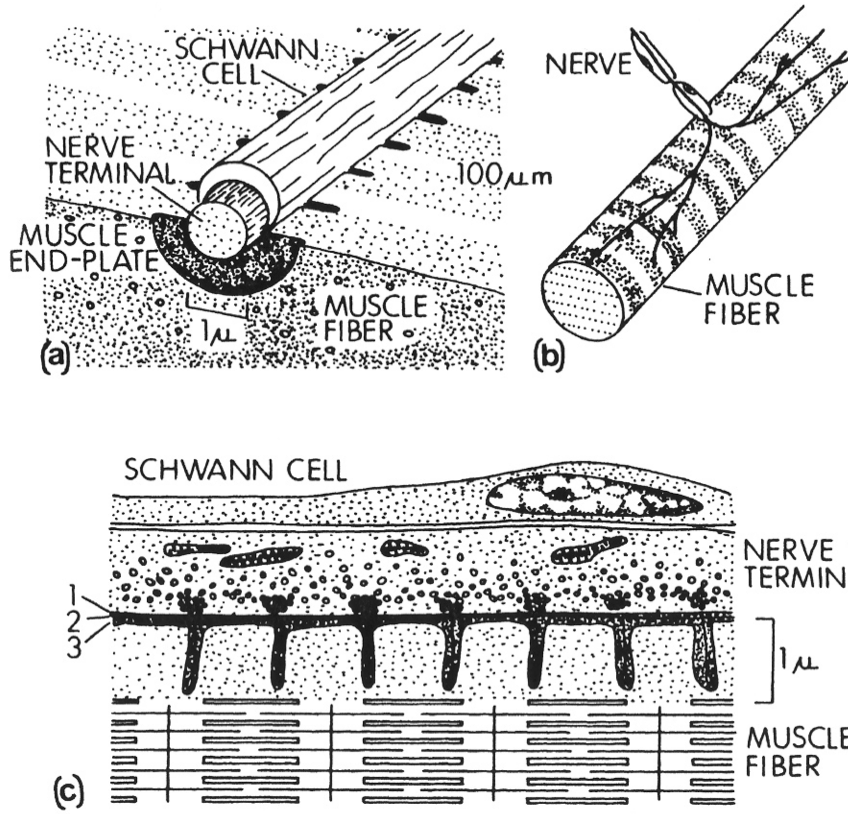


Figure 10.2. Neuromuscular junction of frog. (a) One portion of the junction. (b) General position of endings of motor axon on muscle fiber, showing portion (a) as a small rectangle. (c) Schematic drawing from electron micrographs of a longitudinal section through the muscle fiber. 1, terminal axon membrane; 2, “basement membrane” partitioning the gap between nerve and muscle fiber; 3, folded post-synaptic membrane of muscle fiber. (From B. Katz, *Nerve, Muscle, and Synapse*, McGraw-Hill, New York, 1966. Copyright 1966, McGraw-Hill with permission of the McGraw-Hill companies.)

Structure of the neuromuscular junction (cont.):

The pre- and post-synaptic membrane formations are similar to nerve-to-nerve chemical synapses, except for the synaptic gutter.

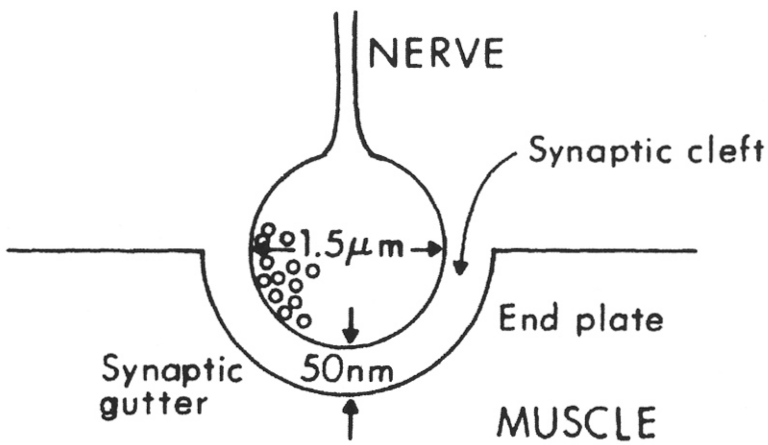


Figure 10.3. Details of the neuromuscular junction at a single nerve terminal.

Steps in muscle fiber contraction

1. Motor neuron action potential
2. Action potential propagation along motor axon (myelinated fiber)
3. Transmission of *acetylcholine* (ACh) at neuromuscular junctions (synapses)
4. Action potential generation in muscle fiber
5. Release of Ca^{2+} from *sarcoplasmic reticulum* initiates attractive forces between actin & myosin filaments, causing them to slide alongside each other) muscle contraction
6. Return of Ca^{2+} to sarcoplasmic reticulum, ending muscle contraction

Muscle structure (cont.):

Each fibril is surrounded by:

- a *sarcoplasmic reticulum* (SR), which stores Ca^{2+} for triggering muscle fiber contraction, and
- the *transverse tubules system* (TTS), which ensures that action potentials propagate deep into the fiber.

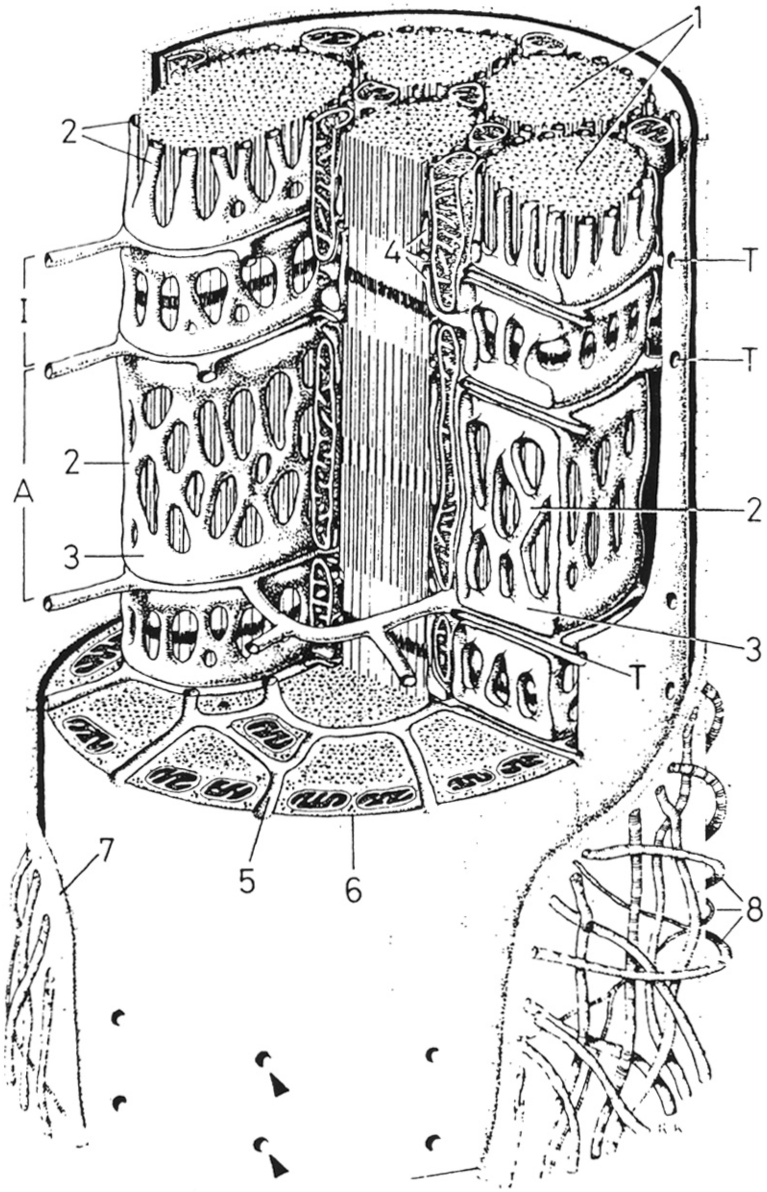


Figure 11.2. A magnified view of the structure of a single muscle fiber with a cutaway view of the myofibrillar structure. Each fibril is surrounded by a sarcoplasmic reticulum (SR) and by the transverse tubules system (TTS) which opens to the exterior of the fiber. [From R. V. Krstić, *Ultrastructure of the Mammalian Cell*, Springer-Verlag, Berlin, Heidelberg, New York, 1970 with permission.]

Actin & myosin filament movement:

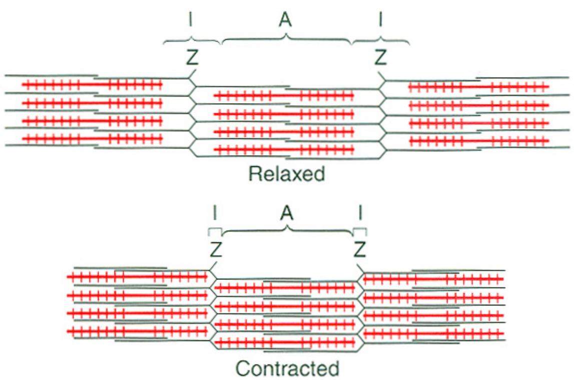


FIGURE 6 – 4

Relaxed and contracted states of a myofibril showing (*top*) sliding of the actin filaments (*black*) into the spaces between the myosin filaments (*red*), and (*bottom*) pulling of the Z membranes toward each other.

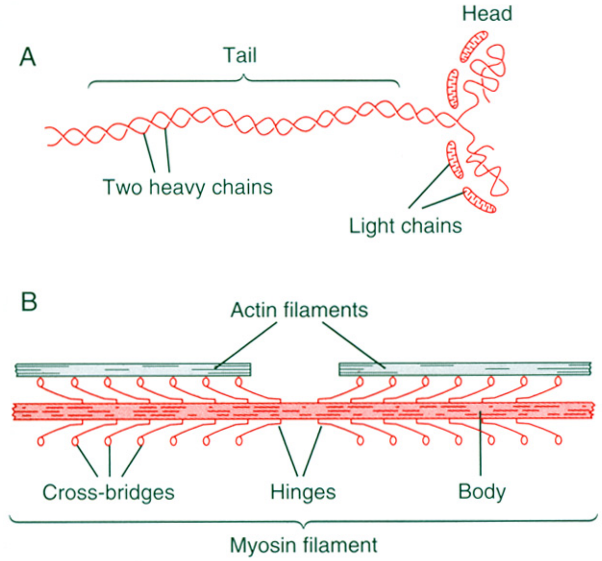


FIGURE 6 – 5

A, Myosin molecule. *B,* Combination of many myosin molecules to form a myosin filament. Also shown are the cross-bridges and interaction between the heads of the cross-bridges and adjacent actin filaments.

(from Guyton and Hall, 10th Edition)

Myofibril

- Muscle fibres 10 – 80 μm
- Each fibre has several hundred to several thousand myofibrils
- Each myofibril has 1500 myosin filaments and 3000 actin filaments
- Z-band (attachment of actin filaments) across the myofibril and between myofibrils

Sliding filament theory:

The sliding filament theory suggests that contraction is generated by movement of the myosin filaments against the actin filaments.

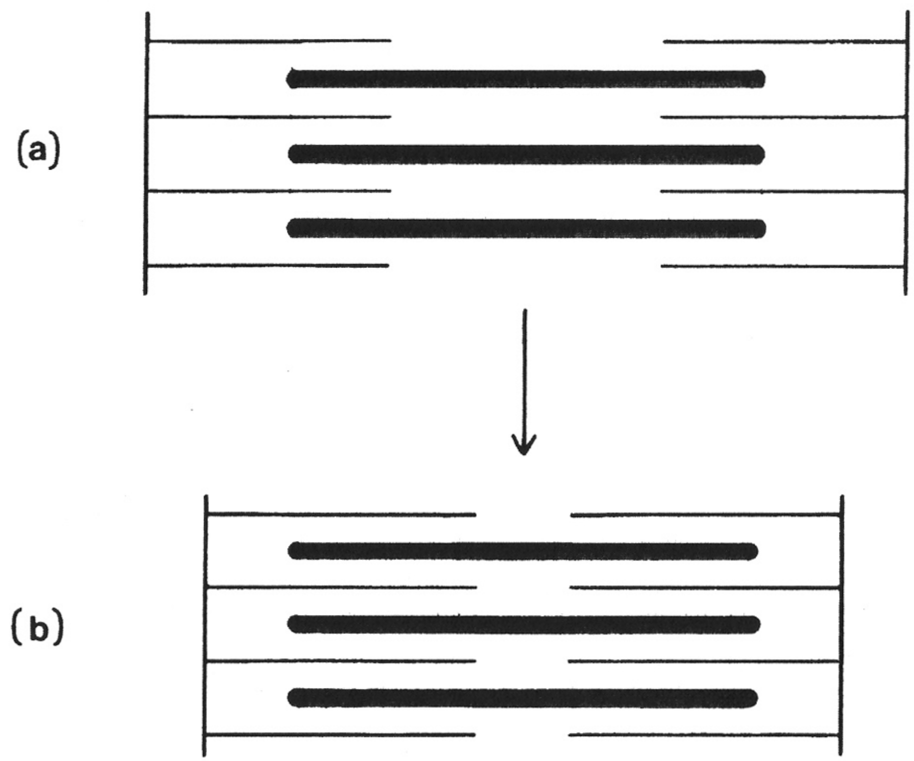


Figure 11.11. The figure illustrates the sliding-filament model. In (a) the muscle is elongated and in (b) it is contracted; in each case the lengths of the thick and thin filaments are unchanged.

Sliding filament theory (cont.):

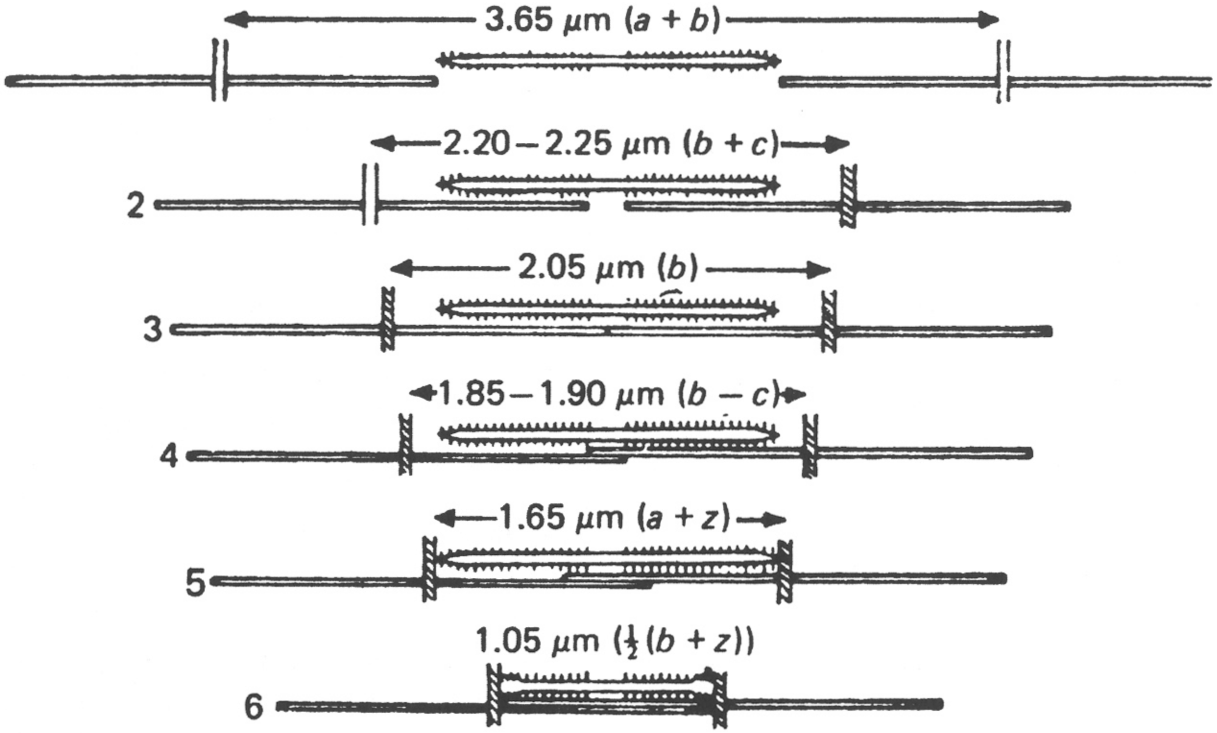


Figure 11.13. Myofilament arrangements at different lengths. The numbers are the positions corresponding to the curve given in Fig. 11.12. a = thick filament length (1.6 μm); b = thin filament length including z line (2.05 μm); c = thick filament region base of projections (0.15 μm); and z = z line width (0.05 μm). [From A. M. Gordon, A. F. Huxley, and F. J. Julian, The variation in isometric tension with sarcomere length in vertebrate muscle fibers, *J. Physiol.* **184**:170–192 (1966). Redrawn by D. J. Aidley, *The Physiology of Excitable Cells*, Cambridge University Press, 1978.]

Sliding filament theory (cont.):

The sliding filament theory is consistent with the tension versus length relationship of muscle undergoing isometric contraction.

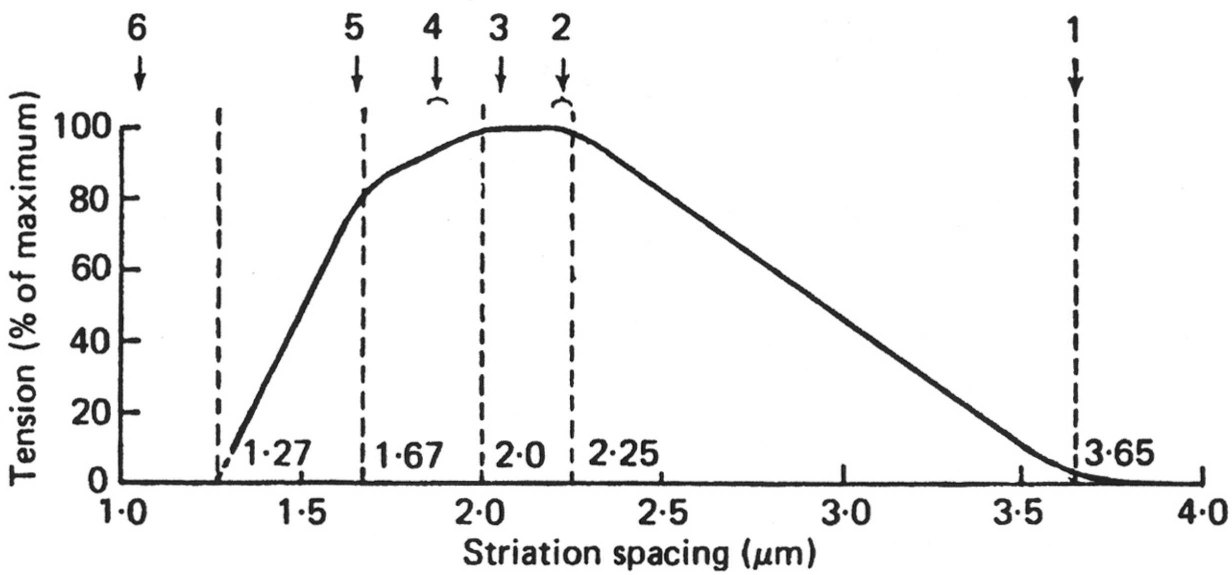


Figure 11.12. The isometric tension of a frog muscle fiber, measured as a percentage of its maximum value at different sarcomere lengths. The numbers 1–6 refer to the myofilament positions illustrated in Fig. 11.13. Note that the general shape is anticipated in Fig. 11.13. [From A. M. Gordon, A. F. Huxley, and F. J. Julian, The variation in isometric tension with sarcomere length in vertebrate muscle fibers, *J. Physiol.* **184**:170–192 (1966). Redrawn by D. J. Aidley, *The Physiology of Excitable Cells*, Cambridge University Press, 1978.]

Fiber types

1. Fast twitch
   - large fibers, for greater contraction strength
   - extensive sarcoplasmic reticulum for rapid release of Ca^{2+}
   - large amounts of glycolytic enzymes
   - less extensive blood supply
   - fewer mitochondria

Force versus velocity:

$$(F + a)(v + b) = (F_0 + a)\,b \qquad (10.7)$$

where F is the contractile force (N), v is the contractile velocity (lengths¢s^{-1}), and F_0, a & b are constants.

F_0 corresponds to the force when v = 0, i.e., during an *isometric* contraction.

$v_{max} = bF_0/a$, when F = 0.

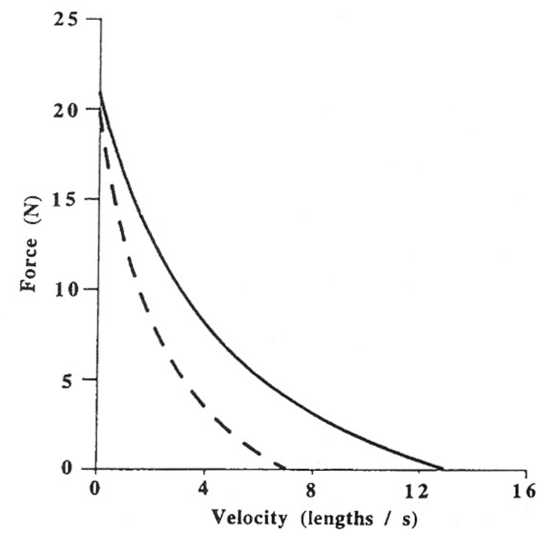


Fig. 10.15 The relationship between force and steady state shortening velocity for a fast-twitch muscle, the rate EDL (solid curve), and for a slow-twitch muscle, the rat soleus (dashed curve), both at 35°C.

Force versus velocity (cont.):

Often the stress value ($P_0 = F_0/A$) is used instead of F_0, where A is the “physiological cross sectional area” obtained by dividing the muscle volume by its length.

P_0 is generally between 100 and 300 kPa, and does not depend on the metabolic fiber type (fast or slow twitch).

However, v_{max} depends on the fiber type.

Force versus fiber length:

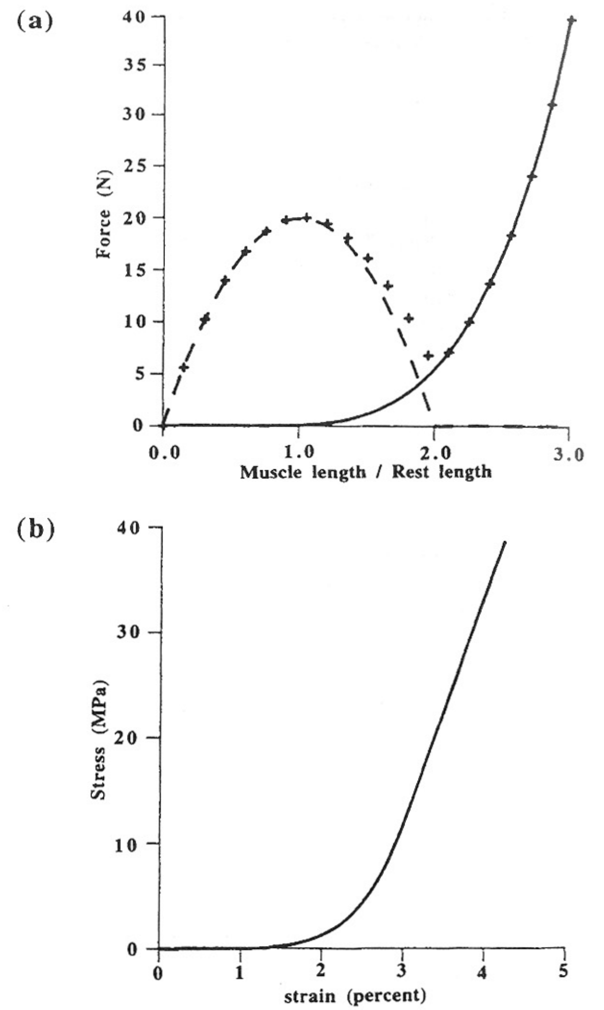


Fig. 10.16 (a) The relationship between length and force for a passive muscle (solid curve), and for an active muscle (+). At each length, the tension developed by active muscle is thought to be the sum of that produced by the passive muscle and the tension produced by the interaction of the sliding filaments (dashed curve). (b) Stress–strain characteristic for a tendon. The characteristic is similar to that for passive muscle, but the tendon is much stiffer.

Force versus fiber length (cont.):

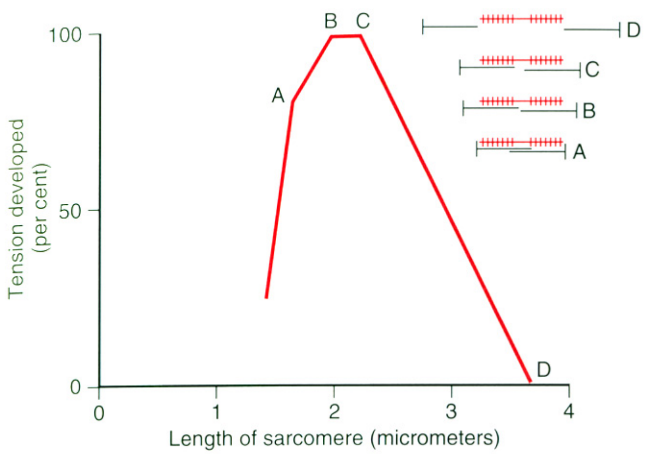


FIGURE 6 – 8

Length-tension diagram for a single sarcomere showing maximum strength of contraction when the sarcomere is 2.0 to 2.2 micrometers in length. At the upper right are shown the relative positions of the actin and myosin filaments at different sarcomere lengths from point A to point D. (Modified from Gordon AM, Huxley AF, Julian FJ: The length-tension diagram of single vertebrate striated muscle fibers. J Physiol 171:28P, 1964.)

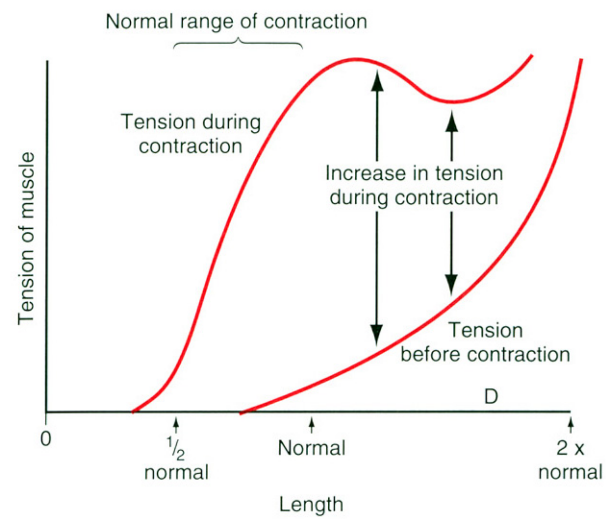


FIGURE 6 – 9

Relation of muscle length to tension in the muscle both before and during muscle contraction.

(from Guyton and Hall, 10th Edition)

Muscle contraction:

A muscle fiber responds to a single neural input with a contractile *twitch*. A fast train of stimuli will twitches that sum together; above the *fusion frequency*, the fiber will be locked in a state referred to as tetanus.

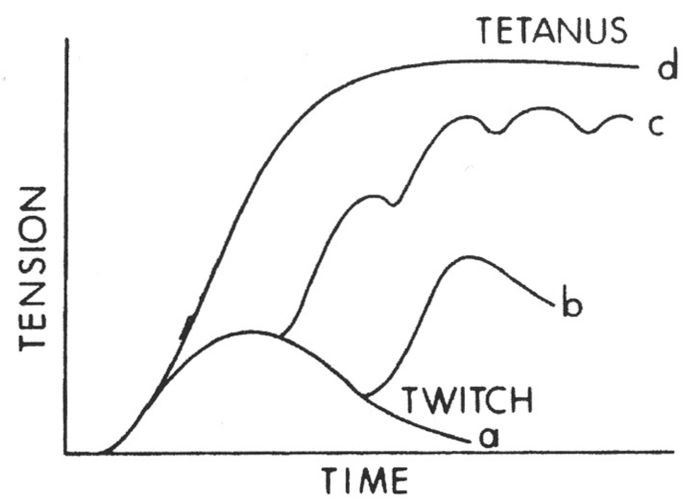


Figure 11.3. Tension versus time for a single stimulus (twitch response) and for a train of stimuli of increasing frequency b, c, d. (From R. D. Keynes and D. J. Aidley, *Nerve and Muscle*, Cambridge University Press, Cambridge, 1981. Reprinted with the permission of Cambridge University Press.)

Force versus activation (cont.):

The total muscle force is modulated by:

– the frequency of twitches in each of a muscle’s motor units) *rate coding*

  and

– the number of motor units being activated) *recruitment*

Hill's model:

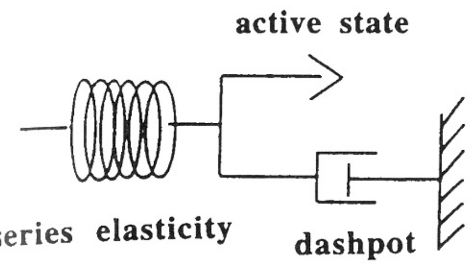


Fig. 10.19 A. V. Hill's model (1938) of muscle mechanics. The 'active state' is a force, which is reduced by the action of the nonlinear dashpot. Together, these form the 'contractile component', which accounts for force production and the force velocity relationship. The 'series elasticity' is necessary to account for the behavior of muscles during quick length or tension changes.

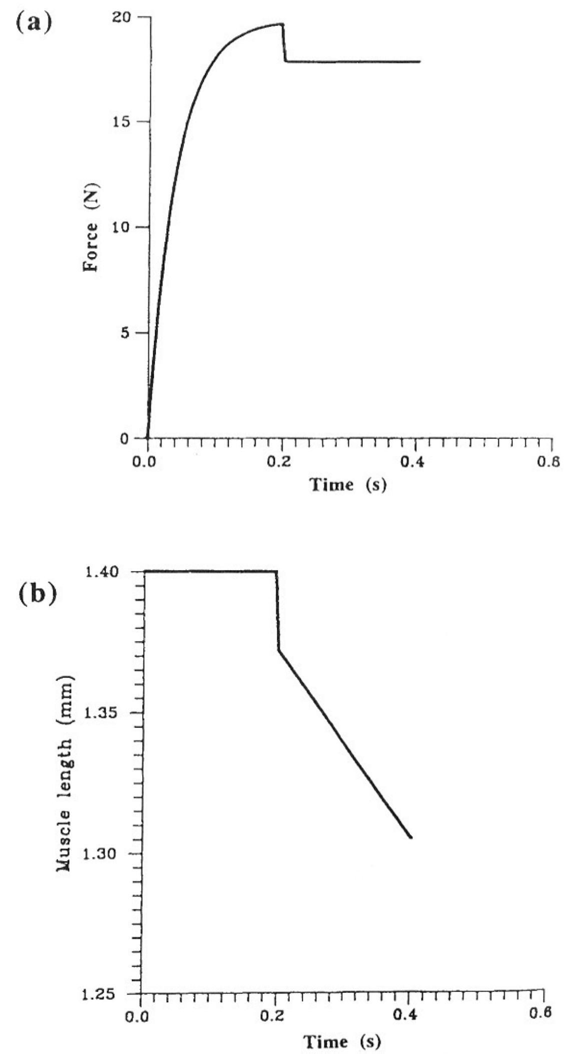


Fig. 10.18 Force (a) and length (b) of a musle subjected to a 'quick release' experiment. The muscle was held at a fixed length and tetanized (rising force). It was then allowed to shorten, lifting the load smaller than F_0. The initial fast length change has been attributed to a 'series elasticity', and the slower length change after it to contraction of the 'contractile element'.

Electromyogram (EMG):

Dynamic

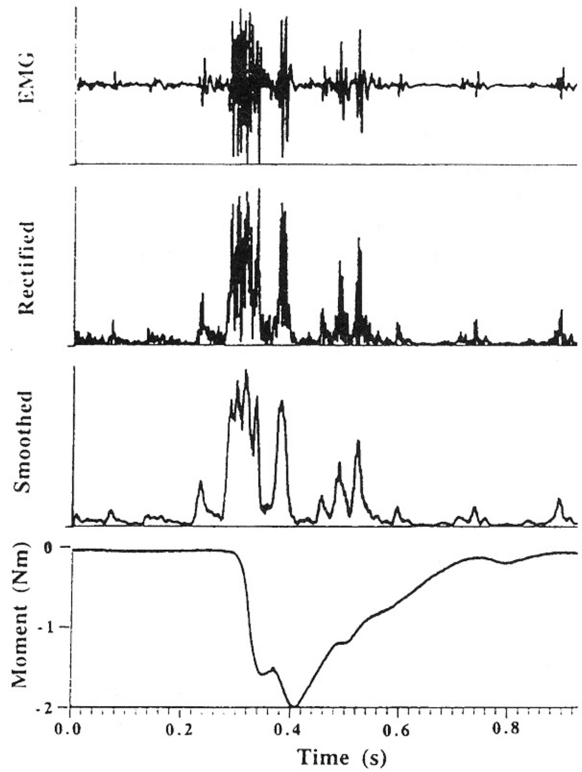


Fig. 10.20 The raw electromyogram is often processed by rectification and smoothing, and is often assumed to vary proportionally with the muscle's 'active state'. In 'phasic contractions', the smoothed rectified EMG does not correlate well with force.

Isometric

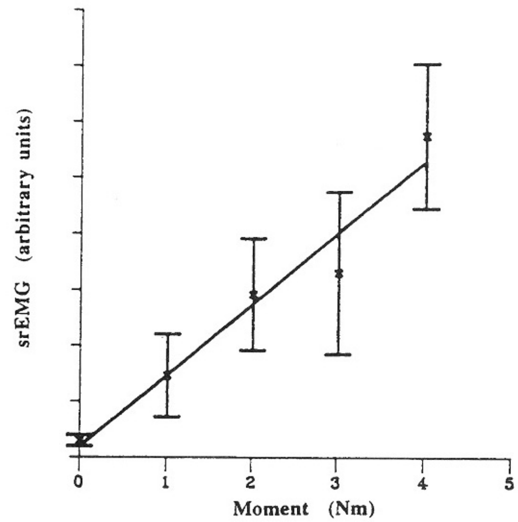
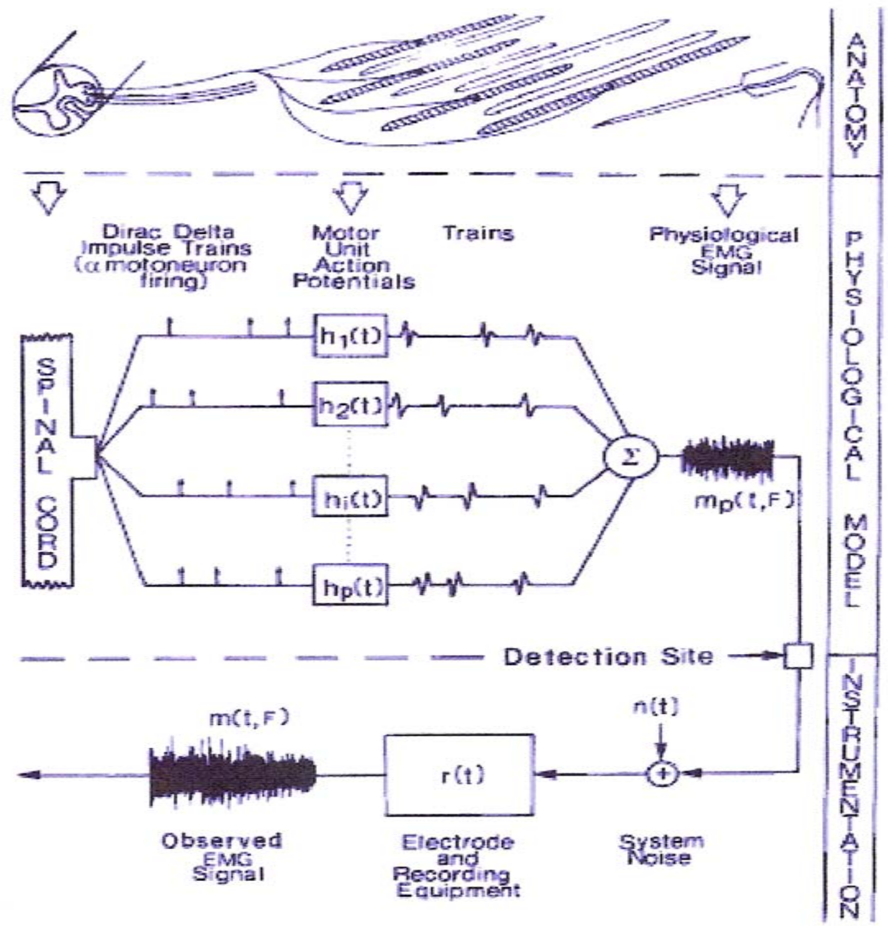


Fig. 10.21 For isometric contractions, integrated smoothed rectified EMG can often be correlated with force.

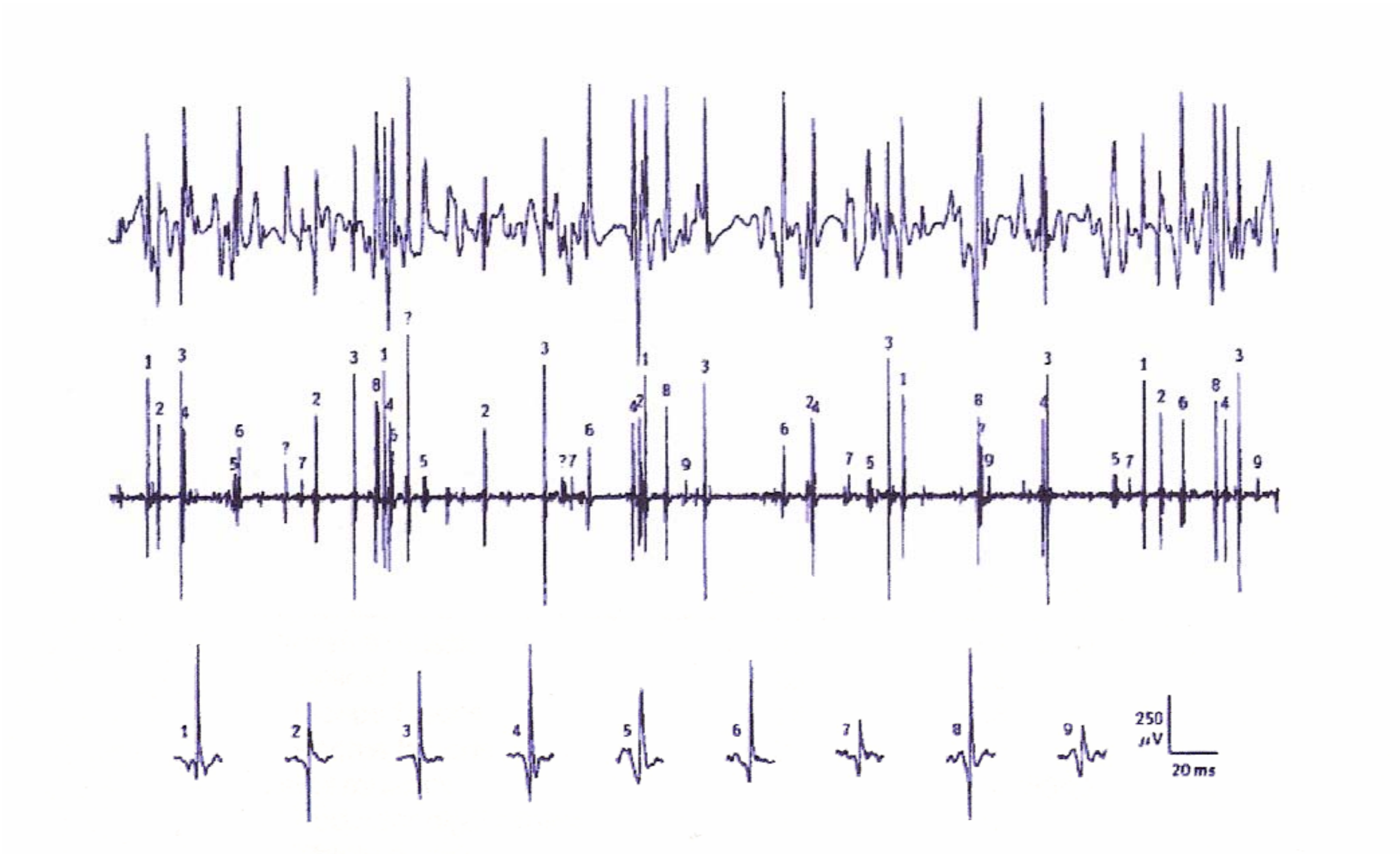
Measuring muscle forces

- strain-gauge tendon transducers
  problem: invasive
- derivation from kinematics and external forces
  problem: often the system of equations is indeterminate, e.g., several flexion and/or extension moments but only one moment equilibrium equation
- electromyography (EMG):
  problem: EMG is usually the sum of several motor unit action potentials) difficult to interpret

Modeling the Electromyographic Signal



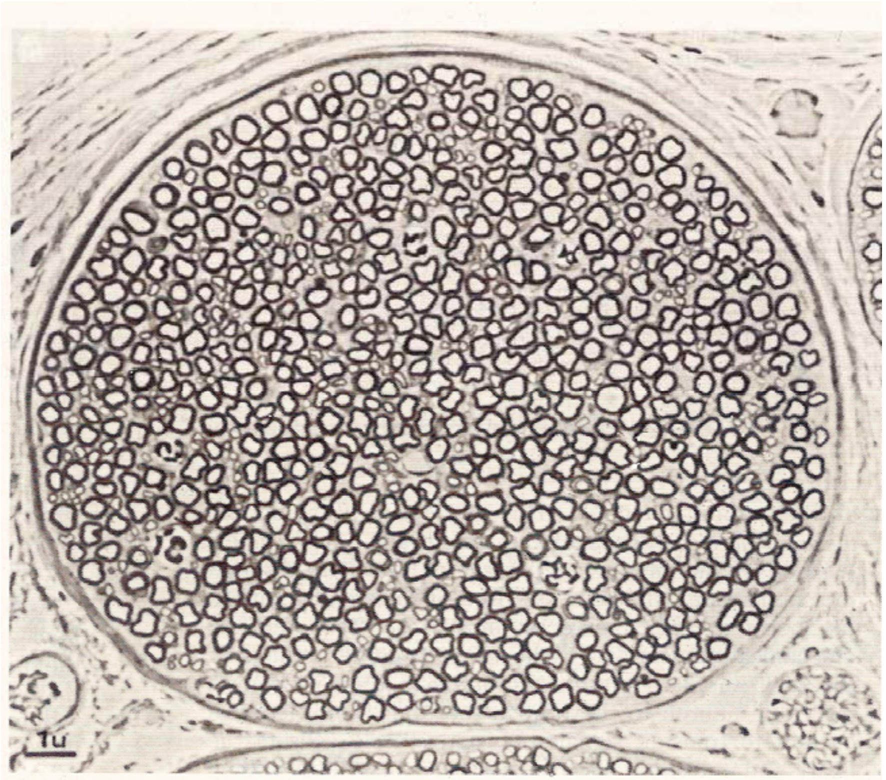
Extracting Motor Unit Action Potentials



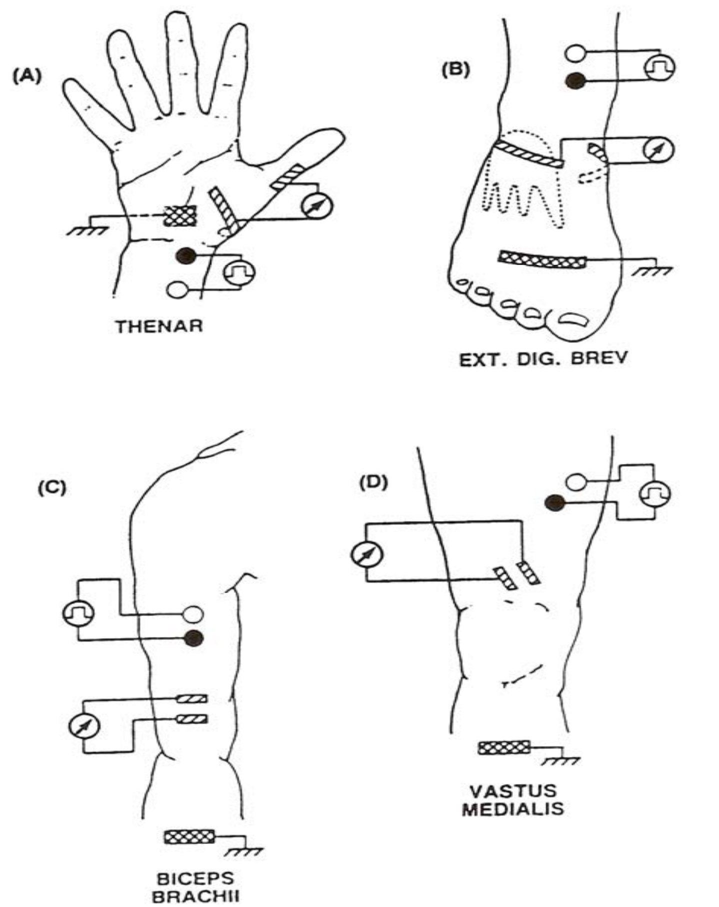
Motor Unit Number Estimation

- Estimate the number of alpha motor neurons
- Determine anatomy of normal nerves and muscles
- Determine presence and extent of neuronal disease (diagnostic)
- Monitor disease progression or response to therapy (drug trials, etc)

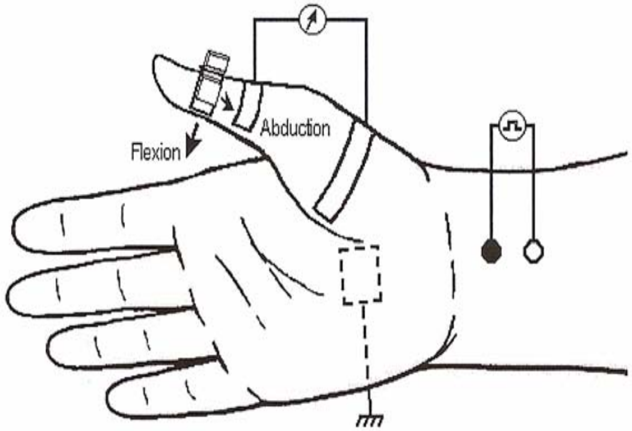
Peripheral Nerve

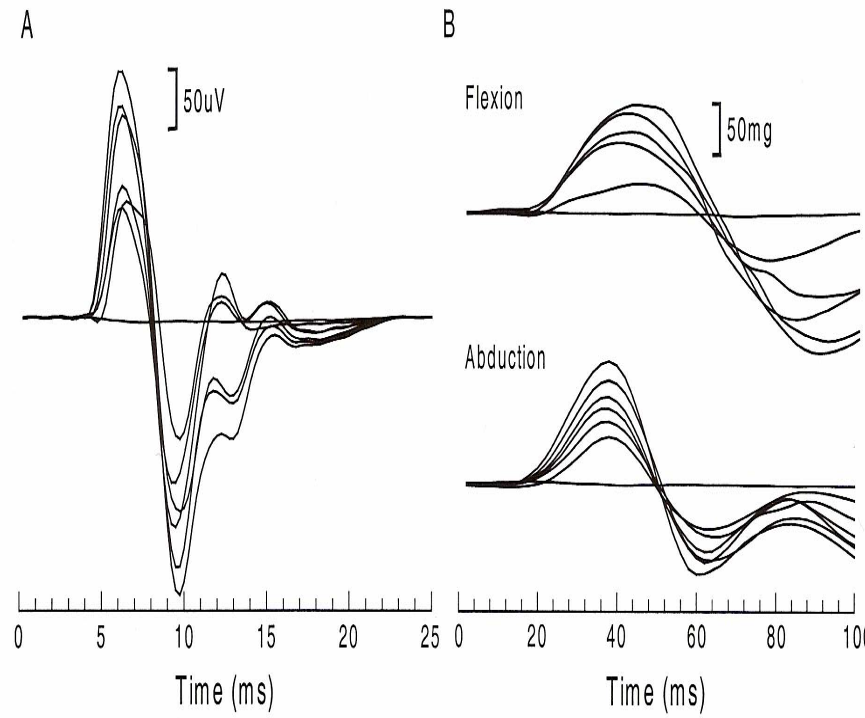


Patient Instrumentation

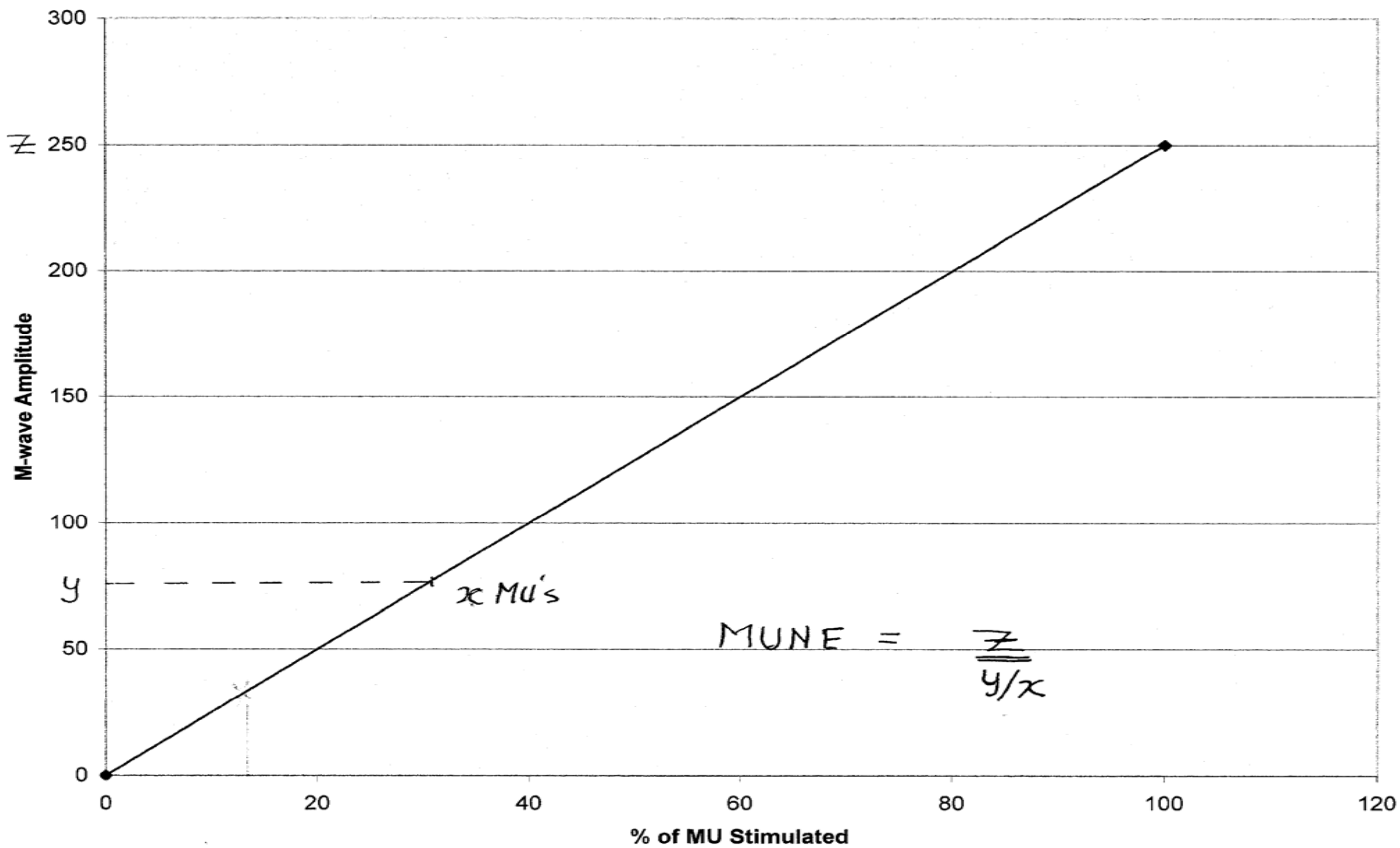


Motor Unit Electrical and Mechanical Responses

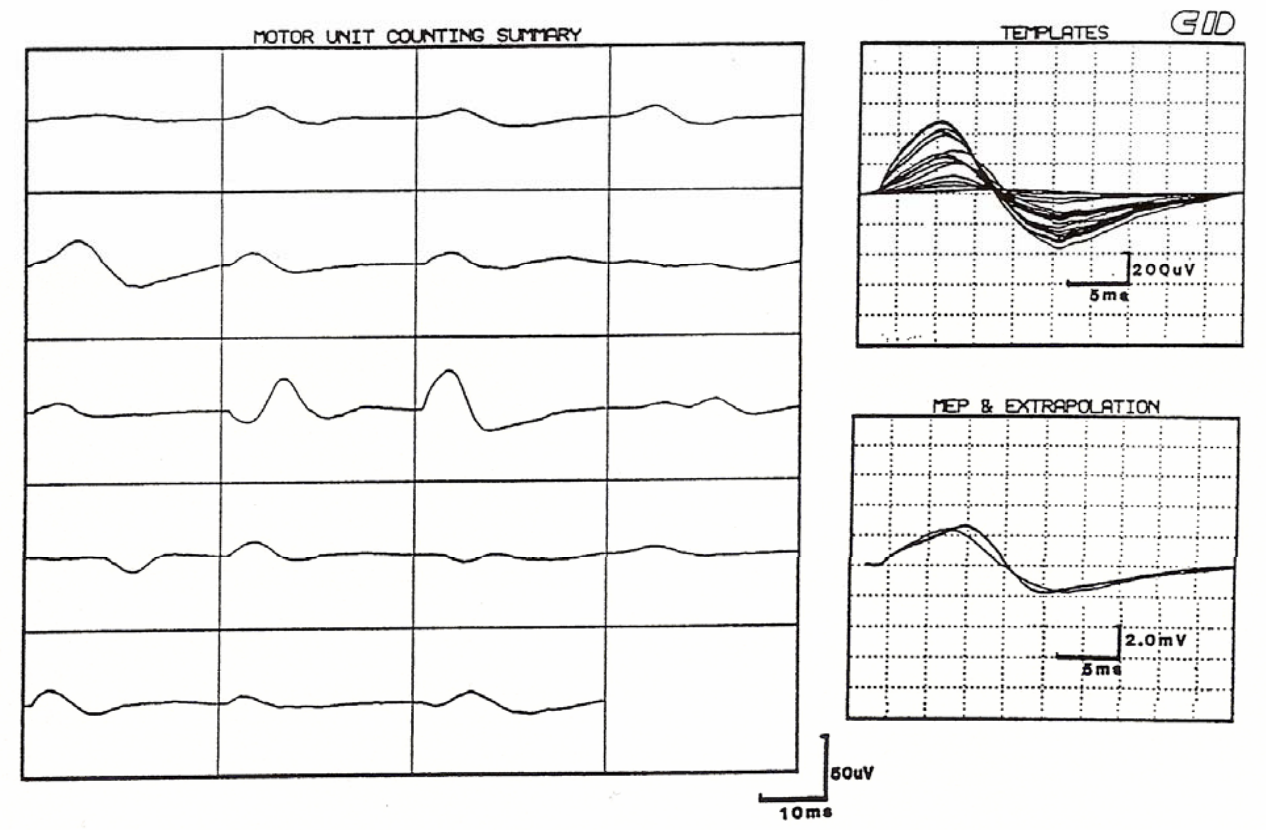




MUNE Calculation



Automated MUNE



Distribution of Motor Unit Potentials

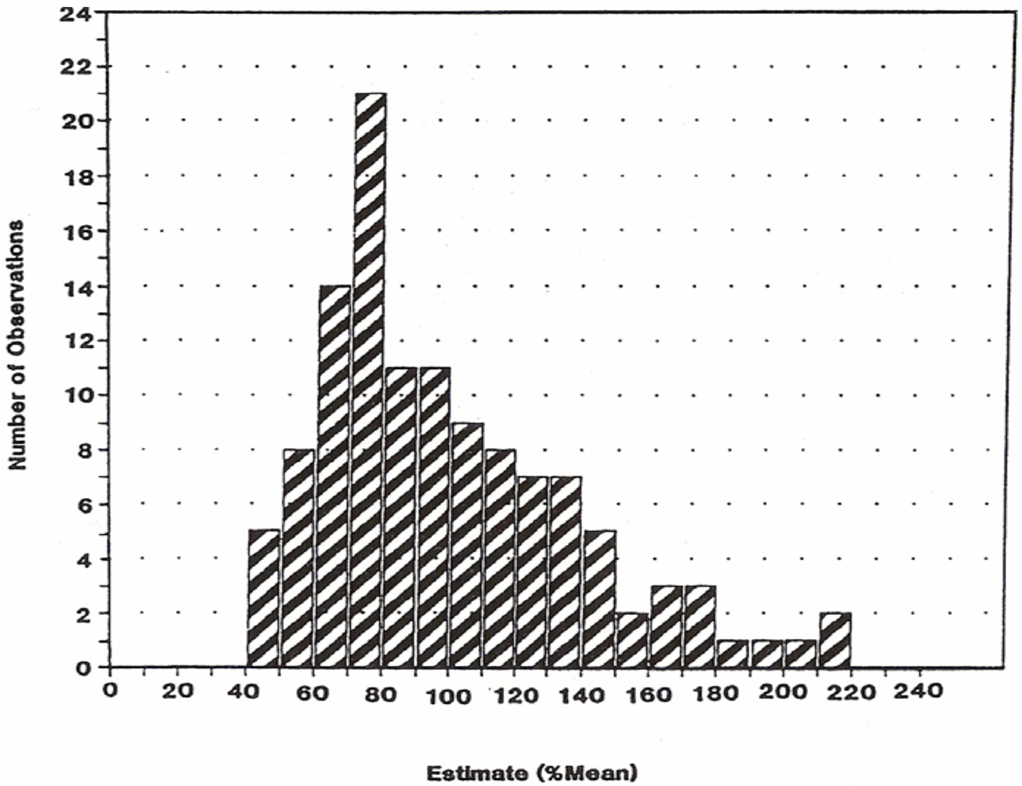
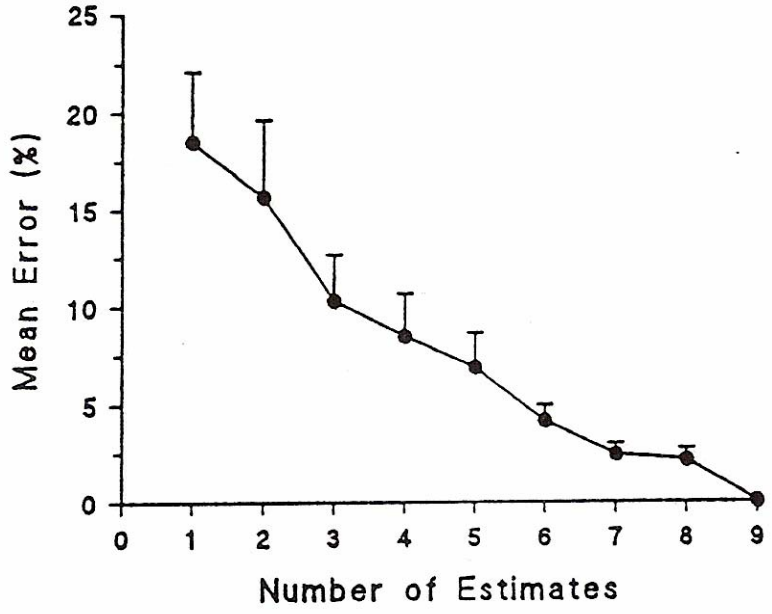


FIGURE 5. Frequency distribution of normalized motor unit estimates for the 4 muscles.

Reliability of Estimates



Results in ALS