Physiology of the peripheral motor system

Timothy J. Doherty, MD, PhD, FRCPC
Depts. of Clinical Neurological Sciences and Physical Medicine and Rehabilitation
Objectives

- Review the basic anatomy of the peripheral nervous system
- To understand the concept of the MU and know basic MU properties
- To know Henneman’s size principle of MU recruitment
- To understand how the MU produces force
- To appreciate the impact of disease on the motor system
Anatomy of PNS

1. Somatic Nervous System – motor fibers to skeletal muscle, sensory fibers from skin, viscera, muscle and tendon receptors
2. Autonomic Nervous System – generally travel with nerves or vessels and control sweating and blood flow to skin and muscle
Anatomy of PNS

- Dorsal rootlets
- Dorsal root
- Ventral rootlets
- Dorsal root ganglion
- Dorsal ramus
- Ventral ramus
- Ventral root
- Gray and White rami communicantes
- Anterior Horn Cells
### Classes of PNS Efferent Fibers

<table>
<thead>
<tr>
<th>Class</th>
<th>Diameter (μm)</th>
<th>Conduction Velocity (m/s)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A – alpha</td>
<td>12 – 20</td>
<td>65 – 120</td>
<td>Extrafusal fibres</td>
</tr>
<tr>
<td>A – gamma</td>
<td>2 – 10</td>
<td>10 – 50</td>
<td>Intrafusal fibres</td>
</tr>
<tr>
<td>B</td>
<td>1 – 5</td>
<td>4 – 26</td>
<td>Presynaptic auton.</td>
</tr>
<tr>
<td>C</td>
<td>0.2 – 0.5</td>
<td>0.2 – 2.0</td>
<td>Postsynaptic auton.</td>
</tr>
</tbody>
</table>
Muscle Afferents

- **Ia afferents** – nuclear bag and nuclear chain endings detect length and rate of change in length
- **Ib** – golgi tendon organs, detect muscle tension
- **II** – detect muscle length, little rate sensitivity
# Classes of PNS Afferents

<table>
<thead>
<tr>
<th>Class</th>
<th>Diameter (um)</th>
<th>Velocity (m/s)</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>12 – 22</td>
<td>65 – 130</td>
<td>muscle length and rate of change in length</td>
</tr>
<tr>
<td>Ib</td>
<td>12 – 22</td>
<td>65 – 130</td>
<td>muscle tension</td>
</tr>
<tr>
<td>II</td>
<td>5 – 15</td>
<td>20 – 90</td>
<td>muscle length</td>
</tr>
<tr>
<td>III</td>
<td>2 – 10</td>
<td>12 – 45</td>
<td>touch, pain, temperature</td>
</tr>
<tr>
<td></td>
<td>(A-delta)</td>
<td></td>
<td>free nerve endings</td>
</tr>
<tr>
<td>IV</td>
<td>0.2 – 1.5</td>
<td>0.2 – 2.0</td>
<td>small pain fibers, muscle pain, visceral receptors</td>
</tr>
</tbody>
</table>
Normal Nerve

- Large myelinated axons
- Small Myelinated axons
- Unmyelinated axons
Normal nerve

Large myelinated Axon

Small unmyelinated Axons
Motor system schematic

Upper MN
Cortical Neuron & Projections (Pyramidal Tract)

Lower MN
A little history

- Sir Charles Scott Sherrington
- Described concept of MU - reflex work on cats
- “Final common pathway” - 1929
The Motor Unit

Anterior horn cell in ventral horn of cord - lamina IX

Ventral Root

Myelinated Axon

Neuromuscular Junction

Muscle Fibers
MU Organization

MUs arranged in columns

All muscles receive innervation from multiple columns (levels or “myotomes”)

Quads: L2, L3, L4
Biceps: C5, C6
TA: L4, L5
The MU Territory

8 – 10 mm in human biceps from EMG studies
Glycogen depletion technique
Normal
Myosin ATPase

Fibre Type Grouping
MU Numbers & Innervation Ratios

![Diagram showing MU Numbers & Innervation Ratios](image)

- **No. of Muscle Fibers / Motor Unit**
  - Extraocular Muscle
  - Platysma
  - Brachioradialis
  - Lumbrical
  - First Dorsal Interosseus
  - Tibialis Anterior
  - Gastrocnemius

- **No. of Motor Units / Muscle**
  - 3K
  - 2K
Functional Organization of MUs

- MUs are also organized into functional groups within a given muscle.
- E.g. in the biceps supination MUs are grouped, and flexor MUs are grouped.
- This allows for more efficient force generation and smoother motor control.
MU Types

- MUs are often classified into different types
- Classification system is dependant on whether physiologic, histochemical, or biochemical features are measured
- In general MUs are either slow and fatigue resistant or vice versa
Tetanus       Twitch       Fatigue Test

CT 34ms
1g 10.4g 10.4g Type S

CT 24ms
1g 1g 14g Type FR

CT 19ms
1g 14g Type FF

1s 20ms 0.1s
## Motor Unit Types

<table>
<thead>
<tr>
<th>Type</th>
<th>I</th>
<th>IIA</th>
<th>IIB</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td></td>
<td>FR</td>
<td>FF</td>
</tr>
<tr>
<td>SO</td>
<td></td>
<td>FOG</td>
<td>FG</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>I</th>
<th>IIA</th>
<th>IIB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twitch CT</td>
<td>Slow</td>
<td>Fast</td>
<td>Fast</td>
</tr>
<tr>
<td>Twitch Force</td>
<td>Small</td>
<td>Intermediate</td>
<td>High</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Myoglobin</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Capillary Supply</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Mitochondria</td>
<td>Many</td>
<td>Many</td>
<td>Few</td>
</tr>
<tr>
<td>Glycogen</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Oxidative Enzymes</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Glycolytic Enzymes</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>MN cell body</td>
<td>Small</td>
<td>Moderate</td>
<td>Large</td>
</tr>
<tr>
<td>AHP</td>
<td>Long</td>
<td>Moderate</td>
<td>Short</td>
</tr>
</tbody>
</table>

- Marathon: 1500m
- Max Jump: 100 m
MU Types
MU Recruitment - Size Principle
Henneman 1957

Henneman

- Excitatory Input (IA afferents)
- Size of intracellular spike recording from motor neuron
- Axonal CVs

Mainly in unanaesthetized decerebrate cats

Denny-Brown 1930’s
Size Principle
Size Principle

$V = I \times R$ (Ohm’s law)

Voltage of EPSP = current $\times$ resistance

The smaller the neuron, the larger the resistance due to the increased channel density
Size Principle - Human

MUs with smaller twitch tensions and slower contraction times are recruited before larger, faster MUs
Rate Coding

A

50 Hz

Frequency

Dorsiflexion force

100 mN

B

Peak Force (% maximum)

0 20 40 60 80 100

0 20 40 60 80 100

Frequency (Hz)
MU Firing Frequencies

- Onset 5-7 Hz
- Min. sustained 8 – 10 Hz
- Maximum 20 – 40 Hz
Recruitment patterns of MUs

**Figure 34-12** For motor tasks that require a slow increase in force, motor units are gradually recruited one at a time and their firing frequency is increased progressively. Units fire at about 8 Hz when first recruited and their firing rate increases as the load on the muscle increases. The record here is from the extensor digitorum communis of a human subject. (Adapted from Monster and Chan 1977.)

**Figure 3.9** Examples of firing rates of motor units in tibialis anterior during isometric dorsiflexion of the ankle at (A) 80%, (B) 50%, and (C) 30% of maximum voluntary contraction (MVC). The force record (showing plateau) is the thick line. The other three lines show mean firing rates of detected motor units. Firing rates decrease throughout the constant-force interval at all force levels. (Reprinted with permission from de Luca CJ, Foley PJ, Ernm Z. Motor unit control properties in constant-force isometric contractions, J Neurophysiol 1996;76:1503–1516.)
Recruitment - de-recruitment

FIGURE 3.8  A. Recruitment and derecruitment of a motor unit in the extensor carpi radialis of human subjects during isometric imposed-ramp contraction and relaxation. Derecruitment threshold is lower than recruitment threshold. B. Relationship between recruitment and derecruitment thresholds for 20 extensor carpi radialis motor units. Again, the derecruitment threshold is systematically lower than the recruitment threshold. (Modified from Romaguera P, Vedel P, Pagni S. Comparison of fluctuations of motor unit recruitment and de-recruitment thresholds in man. Exp Brain Res 1993;95:517–522.)
Overall force production
Is the recruitment order fixed?

- Are ST units always recruited before FT?
- Cutaneous vibratory stimuli can lower the threshold of FT MUs and raise the threshold of ST MUs (Garnett and Stephens, 1980)
- Varying the task changes the relative recruitment threshold of MUs in a given muscle - eg. biceps supination vx flexion
- Selective activation of FT MUs has been shown in the cat, not consistently in humans
Motor Unit Injury

- Motor neuron
  - ALS
- Axon
  - Trauma
- Myelin
  - Compression injury
- Neuromuscular junction
  - Myasthenia
- Muscle
  - Muscular dystrophy
Motor Nerve Injury

- Neurapraxia
  - focal myelin injury
  - conduction block

- Axonotmesis
  - axonal injury
  - conduction block
  - denervation

- Neurotmesis
  - injury to axon and supporting connective tissue
Electrodiagnosis - Nerve Conduction Studies

M-potential size
Motor nerve CV
Motor nerve conduction studies
Sensory Nerve CS
Electrodiagnosis in nerve injury

Normal

Generalized myelin injury

Focal Demyelination

Axonal loss
Conduction block
Needle EMG
Needle EMG

A. Motor Neuron
Nerve Fiber
Terminal axon branch
Endplate Zone

B. EMG Electrode
Motor Unit Territory

C. Extracellular Muscle Fiber Action Potential

D. Motor Unit Action Potential (MUAP)
Anterior Horn Cell or Axonal Injury

With complete nerve resection electrically inexitable in 3 - 5 days

Needle EMG will show spontaneous “Fibrillations” and “Positive Sharp Waves” - Indicates denervation
MU Remodeling
MU Remodeling and the MUP

18 months
MU Remodeling

Strength preserved despite a decrease in MU number

MU Remodeling
Post-polio syndrome

Normal: Four normal motor units are presented. Normal motor units show muscle fibers with a fiber type that is determined by the motor neuron that innervates them. Acute post-polio: Invasion of two motor neurons by poliovirus produces degeneration of the affected motor neuron and eventual denervation of associated muscle fibers. Recovery: Recovery after paralytic polio occurs through sprouting from axonal termini from surviving motor neurons with reinnervation of muscle fibers. This process also produces grouping of muscle fibers of a single fiber type (fiber-type grouping). Further recovery can occur through muscle fiber hypertrophy. Post-polio syndrome: Distal degeneration of enlarged post-polio motor units with denervation of muscle fibers is believed to be the most likely cause of post-polio syndrome.