**Posterior Parietal cortex**
Transforming visual cues into plans for voluntary movements

**Motor cortex**
Initiating, and directing voluntary movements

**Basal ganglia**
Learning movements, motivation of movements, initiating movements

**Cerebellum**
Learning movements and coordination

**Brainstem Centers**
Postural control

**Spinal cord**
Reflex coordination

**Thalamus**

**Motor neurons**

**Skeletal Muscles**
Divisions of the spinal cord:

Cervical
Thoracic
Lumbar
Sacral
A spinal segment
Spinal Cord Injury

- Initial damage is likely limited to a small region
- Hemorrhaging from broken vessels swells the cord, putting pressure on healthy neurons
- Injured neurons release glutamate at very high levels, over exciting neighboring neurons
- Cyst and glutamate kill myelin producing cells
- After a few weeks, a wall of glial cells forms
Most common type of spinal injury in humans: C5-C6

Finger muscles are controlled by motorneurons at C6 or lower.

<table>
<thead>
<tr>
<th>Spinal segment</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
<th>C8</th>
<th>T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scapular muscles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>trapezius</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>levator scapulae</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>rhomboids</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>serratus anterior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thoraco-humeral muscles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pectoralis major</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pectoralis minor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>latissimus dorsi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>teres major</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gleno-humeral muscles</td>
<td></td>
<td></td>
<td></td>
<td>supraspinatus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>infraspinatus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>subscapularis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>teres minor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>deltoid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>coracobrachialis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elbow flexors</td>
<td></td>
<td></td>
<td></td>
<td>biceps</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>brachialis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>brachioradialis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elbow extensors</td>
<td></td>
<td></td>
<td></td>
<td>triceps</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>anconeus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pat Crago, Case Western Reserve Univ.
Neural Prosthetics

Functional Electrical Stimulation to produce a grip
C6 injury: Elevation of shoulder on the left arm signals the stimulator to produce a grip.
Restoration of Grasp and Release of a Tetraplegic Hand Using an FES Neuroprosthesis
Motor neurons reside in the ventral region of the gray matter of the spinal cord. They collect into pools that innervate a single muscle.
A motor unit: a motor neuron and all muscle fibers that it innervates

Motor unit size depends on function
## Polio

Poliovirus invades the motor neurons, killing them.

Muscle fibers in the motor unit are paralyzed.

Neighboring motor neurons grow sprouts to take over orphaned fibers, creating a giant motor unit.

## Motor stroke

Damage to the brain causes loss of neurons that descend to the spinal cord. The resting discharge of motor neurons is severely reduced.
Extrafusal muscle fibers

Intrafusal muscle fiber (contractile component)

γ motor neuron axon

Spindle afferent axons

Tendon

Extrafusal muscle fibers

Intrafusal muscle fiber (sensory component)

α motor neuron axon
Force produced by a muscle depends on the rate of action potentials from the motor nerve.

Kandel ER et al. (1991)
Force produced by a muscle depends on its length.

Force produced through direct electrical stimulation of the soleus muscle of a cat. This muscle’s function is to extend the ankle.
Muscles are organized in an “antagonistic” architecture.

To rapidly move a limb, antagonist muscles are activated in sequence.
Rapid wrist flexion: agonist-antagonist-agonist activation pattern

Britton et al. 1994
Essential tremor: a cerebellar condition associated with delayed 2nd agonist burst

Normal

Essential tremor

Wrist position

Wrist velocity

Wrist flexor EMG

Extensor EMG

30°

500°/s

200 µV

100 µV

200 ms

Britton et al. 1994
Types of Muscle Fibers

In adult humans, we find that a muscle may be made up of 3 distinct kinds of muscle fibers, where each fiber has a particular isoform of the myosin molecule.

- **Type I**: slow contracting fibers. Repeated stimulation results in little or no fatigue (loss of force).
- **Type II**: fast contracting fibers
  - Type IIa: fatigue resistant
  - Type IIx: easily fatigued

Composition of fiber types in a muscle depends on its function.
Types of Motor Units

Three different motor neurons are stimulated intracellularly. A: Twitch response. B: Tetanic stimulation response. C: Tetanic stimulation for 330 msec, repeated every second.

RE Burke and P Tsairis, ANN NY ACAD SCI 228:145, 1974
Change in a Muscle: Spinal Cord Injury & Effect of Exercise

Strength training puts stress on tendons, signaling proteins to activate genes that make more myosin, resulting in the enlargement of muscle fiber. Type IIx fibers are slowly transformed into type IIa fibers.

Paralysis: Transformation of type I fibers into type IIx.

![Graph showing percentage of muscle fiber types for different individuals.](image-url)
Control of Muscle Force

• As more force is need, more motor neurons are recruited.
• Frequency of activation of motor neurons is increased.

Motor units that are activated later tend to produce more force and have faster contraction time.

Use dependent change in a motor unit recruitment: effect of handedness

Muscles of the dominant hand are used more, and so should have larger proportion of type I muscle fibers. To produce a given amount of force, a muscle that has a large number of type I muscle fibers will recruit a proportionally large number of motor units.

Distribution of motor unit recruitment threshold in dominant (D) and non-dominant (ND) hands. The task is isometric force production in the 1st dorsal interosseous muscle.
Muscle’s sensory system allows the CNS to measure force and length of the muscle

(Ia and II afferents)
(Gamma motor neuron)

(Ib afferents)

Alpha motor axon
Extrafusal muscle fiber
Muscle spindle

Spindle afferents
and efferents

Tendon organ afferent

Golgi tendon organ

Tendon

Houk et al. (1980)
Spindle afferents signal length change in the muscle
Golgi tendon afferent signal force change in the muscle

Response of a muscle spindle afferent to an isotonic stretch

Response of a Golgi tendon afferent to an isometric increase in force
Our sense of limb position is via muscle spindles

Elbows on a table, eyes closed. Right hand pulling a string attached to the ceiling. Task is to match position of the right arm with the left arm.

Right biceps is vibrated but remains stationary.

The tracking arm (left arm) becomes extended.
Gamma motor neurons control the sensitivity of the spindle afferents

Spindle is in parallel to the extrafusal muscle fibers.

Stimulation of the $\gamma$-motor neuron shortens the spindle. This results in increased firing in the spindle afferent.

Spindle is sensitive to both $\gamma$-motor neuron input and the length of the extrafusal muscle.
Spindle afferents excite $\alpha$-motor neurons of the same muscle

Golgi tendon afferents inhibit (via inter-neurons) $\alpha$-motor neurons of the same muscle
Hammer tap stretches tendon which, in turn, stretches sensory receptors in leg extensor muscle.

2 (A) Sensory neuron synapses with and excites motor neuron in the spinal cord.

2 (B) Sensory neuron also excites spinal interneuron.

2 (C) Interneuron synapse inhibits motor neuron to flexor muscles.

3 (A) Motor neuron conducts action potential to synapses on extensor muscle fibers, causing contraction.

3 (B) Flexor muscle relaxes because the activity of its motor neurons has been inhibited.

4 Leg extends.
Time delay in the Reflex Loop Pathways

Task: biceps is suddenly stretched at time (S). Before the stretch, subject is instructed to either oppose the stretch (left), or assist it (right).

Delay in fastest reflexes is 30 msec.
The pathways for short- and long-latency response to a perturbation

Short-latency pathway

Long-latency pathway
Time delays in the long latency reflexes

Ankle of a subject is suddenly stretched.

Evoked potential from somatosensory cortex (recorded by EEG electrode)

Evoked potential (recorded with EMG electrode from the ankle dorsiflexor muscle) when motor cortex of same subject is stimulated via magnetic stimulation

EMG recorded when ankle dorsiflexor muscle is suddenly stretched

Delay between spindle afferent and cortex: 46 ms

Delay between cortex and muscle: 30 ms

Ankle position: 94 ms

100 μV

4 deg

20 ms

Petersen et al. J Physiol 1998
Absence of long latency reflexes in a patient with right brainstem stroke

Brief stretch of thumb flexor muscle (at time zero) in a patient with lesion in the dorsal aspect of the right caudal medulla (stroke). Patient has no sense of position or two point discrimination on the right hand, but is normal on the left hand.
Patients without large fiber afferents can move their limbs

Rapid thumb flexion with visual feedback of the hand

- Normal
- Deafferented

Position

Velocity

Thumb flexor muscle

Thumb extensor muscle
Without afferents, vision is necessary to maintain limb posture

Rapid thumb flexion without visual feedback of the hand

Normal

Patient

Position

15°

Vision off

Target

Vision off