Motor Systems (BME 7014)

Dr. Hugo Bergen, Ph.D.
Dept. Human Anatomy & Cell Science
Faculty of Medicine
E-mail: Hugo.Bergen@umanitoba.ca
Motor Control (and Pathways Involved)

• The CNS sites involved in the regulation of voluntary motor activity are:
  1. Cerebral Cortex
  2. Basal Nuclei
  3. Cerebellum
  4. Brainstem nuclei (e.g., Retic. Form., Vestib. N.)
  5. ‘Lower Motor Neurons (LMNs)’ of spinal cord that project to muscles to produce movement (we’ll ignore brainstem cranial nerves for now)
Motor Control: Cerebral Cortex

• The cerebral cortex (includes primary motor cortex, premotor area, supplementary motor area) projects to the lower motor neurons of the spinal cord

• The axons of these neurons descend (as projection fibres) through the diencephalon, brainstem, and spinal cord to travel in descending tracts to LMN or interneurons

• Descending projections to the LMNs are referred to as ‘Upper Motor Neurons (UMNs)’
Motor Control: Cerebral Cortex

• The majority (~85%) of these descending axons cross the midline at the junction of medulla and spinal cord to form the lateral corticospinal tract.
• This tract is the major component of the ‘lateral motor system’.
• The lateral motor system is responsible for movement of the extremities.
• The ~15% that do not cross the midline form the anterior corticospinal tract (component of the ‘medial motor system’).
Lateral Motor System

- Located in lateral white matter of spinal cord
- Responsible for adjusting fine motor activities of the distal limbs
- Supplies contralateral LMN in the spinal cord
- Comprised mainly of 1 tract from the brain:
  1. Lateral Corticospinal tract (motor ctx to spinal cord); projects to the contralateral spinal cord
  2. Rubrospinal (originates from red nucleus of midbrain) tract is sometimes mentioned, but of limited importance
Representation of the lower motor neurons and upper motor neurons of the lateral corticospinal tract

Note: The lateral corticospinal tract (see below) is the largest component of the ‘lateral motor system’.
Lateral Motor System

• Also a corticonuclear tract; analogous to corticospinal tract
• Responsible for controlling voluntary motor activities associated the cranial nerves
• Supplies LMNs in the brainstem for:
  1. CN V: muscles of mastication
  2. CN VII (muscles of facial expression
  3. CN IX and CN X: muscles of swallowing and speech
  4. CN XII: muscles of tongue movement
Spinal Cord

Cortex

Brainstem

UMNs

Decussionation
(crossing of midline)

LMNs

Spinal Cord

Lateral Corticospinal Tract

Anterior Corticospinal Tract
Motor Control: Brainstem

• Brainstem neurons also project to the LMNs of the spinal cord as UMNs.
• Originate from vestibular nuclei (important for balance) and reticular formation (provides pattern generation for initiation of walking)
• Descend in the medial part of the cord as the **medial motor system** (movement of the postural muscles and core for balance and locomotion)
Medial Motor System

- Located in **medial white matter** of spinal cord
- Responsible for adjusting gross motor activities of the axial & girdle muscles that control posture and proximal movements
- Supplies LMNs of the ipsilateral and contralateral side
- Constantly operates to maintain upright body posture and equilibrium, as well as reflexive movement patterns such as coordinated eye/head movements
Medial Motor System

- Comprised of tracts originating from the cortex and the brainstem. The principal tracts are:
  1. **Anterior corticospinal tract**: from cortex to spinal cord for bilateral innervation of axial and girdle muscles
  2. **Reticulospinal tract**: from reticular formation to spinal cord for providing automatic adjustments for posture and gait related movements
3. **Vestibulospinal tracts**: from
   
   i. vestibular n. to cervical spinal cord for head and neck movements in response to vestibular information
   
   ii. vestibular n. to spinal cord for maintaining balance (esp. limb extensor muscles)
Vestibulospinal Tract

Reticulospinal Tract

Vestibular Nuclei

Reticular Nuclei

Brainstem

LMNs

UMNs

Spinal Cord

Cortex

From: Neuroanatomy through Clinical Cases (2nd Ed.) by Blumenfeld. © 2010, Sinauer. Fig. 6.11
Medial motor pathways. The medial vestibulospinal tract is omitted for clarity. Black filled neurons are inhibitory, black open neurons excitatory. Red neurons are lower motor neurons.

Lesion Effects: Unilateral lesions generally produce little in the way of obvious deficits. This is because most of the LMNs that they innervate are innervated bilaterally.
Motor System so far:

- UMN arise from cerebral cortex & brainstem and descend in the white matter of the spinal cord to innervate LMNs.
- Lateral motor system (control of the motor activity of the arms and legs) is located in the lateral part of the spinal cord (mainly lateral corticospinal tract).
- Medial motor system (control of the motor activity of the muscles for posture and locomotion) is located in the medial part of the spinal cord (includes anterior corticospinal, vestibulospinal, and reticulospinal tracts).
Corticospinal Tract (UMN)

- CS tract also referred to as “Pyramidal tract”
- Important for: i) fine movements of limb and face, and ii) control of neck, shoulder, and trunk muscles (posture).
- Note: CS tract crosses the midline at the junction of the brainstem and spinal cord.
- Lesion above result in contralateral deficits and lesions below decussation produce ipsilateral deficits
UMN & Cortical Areas: Lesions

- Lesions commonly result from stroke (involving cortex (cell bodies of UMN), white matter of brain, and spinal cord injury (axons of UMN))
- Lesions result in spastic paralysis or paresis (increased muscle tone / spasticity)
- Hyper-responsive reflexes
- +ve Babinski sign (dorsiflexion of toes)
- Muscle atrophy not present (although this can change over time)
- Note: muscles remain innervated by LMNs
Hyper-responsive Reflexes
Babinski Sign
Lower Motor Neurons (LMNs)

- Cell bodies located in spinal cord & brain stem, but axon synapses directly with skeletal muscle
- Exit spinal cord via ventral root
- Functional unit is the motor unit; i.e., a motor neuron and all of the muscle fibres it innervates
- Damage results in muscle specific dysfunction
Stretch Reflex

Diagram showing the components of a stretch reflex, including the nucleus, nuclear bag fibre, nuclear chain fibre, spindle capsule (cut), la primary afferent, II secondary afferent, y efferent, dorsal root ganglion, la spindle afferent, quadriceps femoris muscle, muscle spindle, tendon, ventral horn of spinal grey matter, al motor neuron, femur, fibula, tibia, patella, patellar ligament.
Motor Unit

Motor nerve axon
Cytoskeleton
Myelin sheath
External lamina
Schwann cell cytoplasm
Primary synaptic cleft
Secondary synaptic cleft
Muscle cell nucleus
Myofibril

Wheater, 2000
Functions of Spinal Cord

- Organization of spinal nerves into sensory (dermatomes) and motor (myotomes) patterns
- Transmission of sensory & motor info. that is subject to modulation and processing
- Integration of circuitry to allow modulation of sensory info.
- Integration of circuitry to allow coordination of motor patterns
- Generates reflexes (integration of ascending sensory info with descending motor commands via interneurons)
Spinal Cord: Internal Anatomy

- Ascending tracts
  - Fasciculus gracilis
  - Fasciculus cuneatus
  - Dorsal spinocerebellar tract
  - Spinothalamic tract

- Descending tracts
  - Lateral corticospinal tract
  - Lateral vestibulospinal tract
  - Pontine reticulospinal tract
  - Ventral corticospinal tract

From: Neuroanatomy: An Illustrated Colour Text (5th Ed.) by Crossman & Neary. © 2015, Elsevier Limited. Figure 8.15
Lower Motor Neurons: Lesions

Cell bodies located in the:
- Brainstem - innervating muscles of the face
- Spinal cord - innervating muscles of the body

If these neurons are lesioned:
1. Flaccid paralysis/paresis (weakness)
2. Loss of reflexes or hypoactive reflexes
3. Muscle atrophy (muscle wasting)
Motor Control Hierarchy

1. **Motor Cortex** (motor areas of frontal lobe): Planning and execution of movement. Source of descending fibres (UMNs) to LMNs of spinal cord (and brainstem cranial nerve nuclei). Lesions result in motor weakness or paralysis.

2. **Basal Nuclei**: initiation and regulation of learned movements. Regulates balance between promoting and suppressing movement. Lesions result in hyperkinetic or hypokinetic disorders.
Motor Control Hierarchy

3. Cerebellum: Timing, coordination and accuracy of movements (esp. fine motor skills). Lesions result in intention tremor, dysmetria, slurred speech and ataxic movements (poor muscle control).

4. Brainstem Nuclei (including vestib. nuclei and reticular formation): Primarily affect axial musculature important for posture and balance and also locomotion.
UMNs

Lateral motor systems

Medial motor systems

To spinal cord

Cerebral cortex

Thalamus

Pons

Brainstem

Basal ganglia

Cerebellum

From: Neuroanatomy through Clinical Cases (2nd Ed.) by Blumenfeld. © 2010, Sinauer. Fig. 6.6
Motor Control by Cortex (Ctx)

Motor ctx consists of 1\textsuperscript{st} Motor ctx, Premotor, and Supplementary Motor ctx.

**A. 1\textsuperscript{st} Motor Ctx:** Located on post-central gyrus of frontal lobe. Source of many UMNs for control of voluntary movement (corticospinal [CS] tract). Body is ‘mapped’ onto gyrus (homunculus). Input from cerebellum.
Motor Control by Cortex (Ctx)

B. **Pre-Motor & Supp. Motor Ctx**: Located anterior to $1^0$ motor ctx. Important for planning movements. Receive inputs from somatosensory ctx and basal nuclei. Projects to $1^0$ motor ctx and also to spinal cord as CS tract.

From: Neuroanatomy through Clinical Cases (2nd Ed.) by Blumenfeld. © 2010, Sinauer. Fig. 6.1
Motor cortex (cont.)

- Controls contra-lateral voluntary movements of face, hand & feet.
- These areas take up a disproportionate amount of motor cortex due to the precision and control required.
- Muscle that act bi-laterally (ie. muscles of stomach & back) are controlled by the motor cortex on both sides.
Motor Cortex (cont.)
Motor Control by Cortex (Summary)

A. 1<sup>0</sup> Motor Ctx: Contains UMNs (CS tract) and receives input from Premotor and Supplementary Motor ctx (these house motor programs / the instructions for movement). Also receive input from cerebellum to ‘fine tune’ activation of UMNs.

B. Pre-Motor & Supp. Motor Ctx: Receive inputs from prefrontal cortex (behavior), SS ctx and basal nuclei. Projects to 1<sup>0</sup> motor ctx and also to spinal cord as CS tract.
Motor Control by Ctx (Summary) (cont.)

B. Pre-Motor & Supp. Motor Ctx:
- Also important for initiation of movement
- Planning of movement
- Programming of the sequencing of muscle activation (extensors/flexors)
Flow of Cortical Information

- Primary sensory cortex
  - Simple sensory discrimination (intensity, quality)
  - Recognition of sensation

- Sensory association cortex
  - Emotions, memory processing

- Association cortex
  - Goal selection, planning, monitoring
  - Interpretation of sensation
  - Movement composition, sequencing

- Motor planning areas

- Primary motor cortex
  - Cortical motor output
Lesions of pre-motor cortex and supplementary motor cortex may produce apraxia; i.e., difficulty in performing ‘motor programs’ such as throwing a ball or combing hair.
Motor Programs

- Random
- Planned & executed
- Planned but not executed
A. **Basal Nuclei**: Receives input from cortex and projects back to cortex (via thalamus) to inhibit or enhance the activity of motor programs. Lesions result in dyskinesias (involuntary movements and tics; hyperkinesias) such as Huntington’s chorea. Also bradykinesia, e.g., Parkinson’s Disease (also characterized by muscle rigidity and tremors). Contains info. on the regulation of stereotypical movements.
Hyperkinetic Gait: Demo
Hyperkinesis: Huntingtons Chorea
Hypokinetic Gait: Demo
Hypokinetic Gait: Parkinsonism
Parkinsonian Walk / Cycle

• See NEJM Video

• http://www.nejm.org/action/showMediaPlayer?doi=10.1056%2FNEJMlc0810287&aid=NEJMlc0810287_attach_1&area=
Motor Control by Subcortical Structures

B. **Cerebellum**: Receives inputs from cortex, spinal cord (proprioception), and vestibular system.
   - Projects to $1^0 \text{ motor ctx}$ (via the thalamus) to regulate the timing, force, speed, and sequencing of motor activity as governed by the descending CS tract.
   - Also acts on descending brainstem tract to aid in maintaining balance (vestibulospinal tract).
   - Lesions result in deficits in fine motor skills (and balance).
B. Cerebellum (cont.):

- Integrates (and compares) sensory information with motor information to produce intended movement
- Regulates movement patterns & posture by adjusting output of descending tracts
- Acts on lateral motor system: projects to cortex
- Acts on medial motor system: projects to reticular formation and vestibular nuclei
Cerebellar Lesion: Video #1
Cerebellar Lesion: Video #2
Cerebellar Lesion: Video #3
Motor Control: Lesions

Assoc. ctx, basal nuclei, and cerebellum do not project to LMNs of spinal cord (act on UMN)
Therefore: lesions of assoc. ctx, basal n., and cerebellum, paralysis or paresis is not present
However: paralysis or paresis is a key feature with lesions of UMN or LMN
Motor System Responsibility

- Coordinating activities of agonist / antagonistic muscle groups (flexors vs. extensors)
- Conveying accurately timed commands to many one or many groups of muscles
- Making postural adjustments and coordinating balance
- Coordinating movements of segments, joints & muscles
- Normal function relies on feed forward / back systems and a hierarchy of control
From: Fitzgerald’s Clinical Neuroanatomy and Neuroscience (7th Ed.) by Mtui, Gruener, & Dockery. © 2016, Elsevier Limited. Fig. 16.4
3 Types of Movement

1. Voluntary
   • Has purpose
   • Is goal directed
   • Involves higher cortical centers
   • Once learned, performance improves with practice
   • Relies heavily on vision and somatosensory systems
3 Types of Movement (cont.)

2. Reflexes
   • Occurs via central commands to LMN
   • Involuntary and controlled via spinal cord and brainstem
   • Important for balance and orientation of head and eyes
   • Uses feed forward / back sensory loops and info from visual, vestibular, and somatosensory systems.
   • E.g., withdrawal reflex
3. Rhythmic Movement Patterns
   • Generally only initiation and termination are entirely voluntary
   • Involves input from all aspects of nervous system (cortex and brainstem and spinal cord circuits)
   • Central pattern generators (CPGs) important for stereotypic repetitious movements (e.g., walking or swimming)
   • CPGs are localized neural networks that include the spinal cord, brain stem, and cerebellum.
   • CPGs can trigger simple repetitive motor activities, in the lower brain stem or spinal cord.
Location of Central Pattern Generators in the CNS

**FIGURE 28.5** Location of different networks (CPGs) that coordinate different motor patterns in vertebrates. The spinal cord contains CPGs for locomotion and protective reflexes, whereas the brain stem contains CPGs for breathing, chewing, swallowing, and saccadic eye movements. The hypothalamus in the forebrain contains centers that regulate eating and drinking. These areas can coordinate the sequence of activation of different CPGs. For instance, if the fluid intake area is activated, the animal starts looking around for water, walks toward the water, positions itself to be able to drink, and finally starts drinking. The animal will continue to drink as long as the stimulation of the hypothalamic area is sustained. This is an example of recruitment of different CPGs in a behaviorally relevant order. The cerebral cortex is important, particularly for fine motor coordination involving hands and fingers and for speech.
Summary of Hierarchy

Level 1: Spinal Cord – location of the motor neurons innervating the muscle and circuits for rhythmic behaviors
Level 2: Brainstem – location of neurons descending in medial motor system
Level 3: Motor Cortex – location of motor programs and neurons descending in lateral motor system
Level 4: Association Cortex – location of higher order functioning (directing behavior)
Hierarchy of Motor Systems

Level 1: Spinal Cord

Level 2: Brain Stem
(Red Nucleus, Reticular Formation, Vestibular Nuclei, Tectum, Pontine Nuclei, Inferior Olive)

Level 3: Motor Cortex
(Primary Motor Cortex, Premotor Cortex, Supplementary Motor Area)

Level 4: Association Cortex

Side Loop 1: Basal Ganglia
(Caudate Nucleus, Putamen, Globus Pallidus, Substantia Nigra, Subthalamic Nucleus)

Thalamus

Side Loop 2: Cerebellum