Basics of Motor Control and Movement

An important part of physiology deals with motor functions, i.e. the ability to move, and how this is made possible by our central nervous system, which controls the skeletal muscles. Motor control involves a complex coordination of several regions of the brain that are hierarchically organized motor systems interacting with each other. In the following article, the basics of the interaction and functioning of these motor systems are explained.

How Is Movement Possible?

Body movement relies on the motor systems located in the spinal cord, brain stem, cerebellum, and cerebrum, which communicate with each other via certain pathways.

Spinal Motor System

The spinal motor system regulates movement coordination at the spinal cord level, including the most basic motor response to a stimulus – the reflex. From a hierarchical point of view, reflexes represent the lowest functional level of motor control.
Reflexes

A reflex is a stereotypical response to a stimulus. A reflex arc consists of the following parts:

- **Sensor**
- **Afferent nerve path**
- **One (monosynaptic) or several (polysynaptic) neurons**
- **Efferent nerve path**
- **Effector**

A registered stimulus travels via the afferent nerve pathway to the motor neurons (anterior horn cells) of the spinal cord, which send the response to the stimulus via their axons (i.e., the efferent nerve pathway) to the effector organ.

**Sensors of the reflex arc**

A fundamental role in motor control is played by proprioception, which describes the reception of stimuli from the internal body through mechanoreceptors. The following sensors are part of the spinal system, each of which is specialized for different stimuli:

**Muscle spindles**

Muscle spindles are stretch sensors of the skeletal muscles and measure **muscle length and stretch rate**. They consist of intrafusal fibers (specialized muscle cells), which are surrounded by a capsule consisting of connective tissue, and are arranged parallel to the skeletal muscles. They can be found more or less frequently in every muscle. In small
muscles, which are important for precision, the number of muscle spindles is particularly high.

**Tendon organ**

Tendon organs are stretch sensors of the skeletal muscles which, in turn, measure the **tension** in the muscles. They are arranged in series to the skeletal muscles and are located at the transition of the tendon to muscle. If the tension in the muscle increases, this stimulus is conducted via the myelinated nerve fiber of the tendon organ over the dorsal root to the spinal cord, which inhibits the motor neurons; therefore the contraction of the muscle is slowed down.

**Sensors in the joints**

Each joint has groups of sensors for the different movement capacities of the joint axis, for example, internal or external rotation.

**Cutaneous sensors**

The afferent pathways of the reflex arcs also contain information from the numerous mechanoreceptors and pain receptors of the skin and from the free nerve endings of the muscles (see: multisynaptic reflex).

**The efferent nerve pathways of the reflex arc: motor neurons**

The motor neurons are located in the anterior horn of the spinal cord. The following motor neurons can be distinguished:

- γ-motor neurons, which innervate the intrafusal muscles (muscles of the muscle spindle).
- α-motor neurons, which innervate the extrafusal muscles (skeletal muscles). They receive information from the sensors of skin, muscles, and joints, from the corticospinal pathways as well as from the spinal cord. α-motor neurons can be distinguished as follows:

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<tr>
<th>Phasic α-motor neurons</th>
<th>Tonic α-motor neurons</th>
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<tr>
<td>Thick axons</td>
<td>Thin axons</td>
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<tr>
<td>High transmission rate</td>
<td>Low transmission rate</td>
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<td>Supply ATP-rich muscle fibers, which quickly contract and fatigue</td>
<td>Supply the muscles of the supporting apparatus</td>
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The α-motor neurons are connected with the **Renshaw cells** via afferent nerve pathways that inhibit motor neuron activity through feedback inhibition.

**Motor endplate**

Motor nerve fibers have a different number of branches in different muscles, depending on how precisely the muscle is working. Each axon of a motor anterior horn cell forms, together with the muscle fibers it supplies, a so-called **motor unit**. Therefore, the muscle fibers supplied by 1 axon all contract at once.

The area where stimulus transmission occurs from the nerve ending to the muscle is called the **motor endplate** (or motor nerve terminal). The endings of the nerve branches do not have any myelin sheaths and the muscle fibers are a bit elevated. The motor endplate is a special synapse in that the excitation is transferred by the chemical messenger substance called **acetylcholine**.
How does the transmission of the excitation at the motor endplate work?

The arriving action potential results in a presynaptic opening of calcium channels, so vesicles containing acetylcholine are released into the synaptic gap. The vesicles release their content through exocytosis, and the acetylcholine binds to the receptors in the postsynaptic membrane, which opens their ion channels. Because of the influx of the ions, muscle cells depolarize – the result is a contraction of the muscle.

Brain Stem Motor System

**Function**: The brain stem, consisting of the medulla oblongata, pons, and midbrain, is a kind of coordinating unit of all motor control. Through the brain stem reflexes, quick adaptation to environmental changes is possible.

The brain stem is connected to the higher regions of the brain, and by the descending pathways coming from its nucleus areas, the motor neurons of the spinal cord are activated or inhibited.

**Important motor nuclei of the brain stem**:
- Red nucleus
- Vestibular nuclei (lateral vestibular nucleus a.k.a. Deiters nucleus; medial vestibular nucleus)
- Parts of the reticular formation

**Important afferent nerve pathways of the brain stem**:
- Motor cortex
- Cerebellum
- Vestibular system

**Important efferent nerve pathways of the brain stem**:
- Rubrospinal tract
- Vestibulospinal tract
- Medial and lateral reticulospinal tract

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<tr>
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The most important reflexes of the brain stem are:
- **Static reflexes** are body righting reflexes, which coordinate the body position in space.
- **Statokineti**cal reflexes, like physiological nystagmus and the elevation-induced labyrinthine tonic reflex, are reflexes that are triggered by movement and ensure that balance is maintained.
- **Reflexes coordinating food intake** are: sucking reflex, salivary reflex, chewing, and swallowing reflex.
Defensive reflexes include the corneal reflex and cough reflex.

Cerebellum and Motor Control

**Function:** Fine motor skills - coordination of supporting and target-directed motor skills and the preparation of motor programs.

The cerebellum receives information from the labyrinth, spinal cord, and the idea of the movement from the motor cortex. Its efferent nerve pathways go from the brain stem via the thalamus to the motor cortex. Its anatomical structure of cortex and marrow with nuclei resembles the structure of the cerebrum.

All pathways coming from the cerebellum go through the nuclei of the cerebellum (fastigial, interposed, and dentate nuclei). The cortex of the cerebellum contains different neurons in its 3 layers that are afferently formed either by climbing fibers from the olive or mossy fibers from other areas.

**The afferent nerve pathways of the cerebellum:**

- The archicerebellum receives information from the vestibular nuclei
- The paleocerebellum receives information from the spinal marrow and the pyramidal tract.
- The neocerebellum receives the concept of movement of the associative parts of the cerebral cortex.

**The afferent nerve pathways of the cerebellum:**

1. Starting from the cerebellar vermis, efferent nerve pathways go through the fastigial nucleus to the brain stem and coordinate muscle tone, balance, and supporting motor skills.
2. The efferent nerve pathways of the intermediate part go via the interposed nucleus and the efferent nerve pathways of the cerebellar hemispheres via the dentate nucleus to the brain stem (red nucleus) and then via the thalamus to the motor cortex of the cerebrum. The intermediate part corrects the planned movement of the motor cortex and coordinates targeting with the supporting motor skills. The hemispheres of the cerebellum make motor programs for fast target-directed movements, based on information from the associative cortex and the concepts of movement planned by the cerebrum. The necessary supporting motor skills are activated through the connection to the brain stem.

Basal Ganglia

**Function:** Control and modulation of complex movements (e.g. writing), which makes harmonic motion sequences possible (motor memory).
Basal ganglia are subcortical nuclei, near the thalamus. They are part of the **extrapyramidal system**. From a functional (not anatomical) point of view, the following structures belong to the basal ganglia:

- Striatum caudate nucleus and putamen)
- Pallidum
- Substantia nigra (in the area of the midbrain)
- Subthalamic nucleus (in the area of the diencephalon)

The basal ganglia receive information from different parts of the cerebral cortex. They generate motor programs for slow movements and adapt speed and the degree of movement to the conditions of the organism. The basal ganglia have either a stimulating or inhibiting effect on motor functions. Thus, it is clear why degenerative diseases of the basal ganglia manifest with excessive movements—like in **Huntington’s disease**—or with akinesia—like in **Parkinson’s disease**.

**Striatum**

**Function:** Inhibition of motor functions

The striatum receives stimulating afferent nerve pathways (mediated by **glutamate**) from the cortex and more inhibiting ones (mediated by **dopamine**) from the substantia nigra. The efferent nerve pathways of the striatum have an inhibiting effect on pallidum and substantia nigra, transmitted by **GABA**.

**Pallidum**

**Function:** Enhances motor skills, ‘antagonist’ of the striatum.

Its afferent nerve pathways come from the striatum, subthalamic nucleus, and thalamus. Efferent nerve pathways go to the thalamus as well as to the cerebral cortex.

**Subthalamic nucleus**

**Function:** Exerts inhibiting effect on motor skills
The subthalamic nucleus is connected to the pallidum through afferent (inhibiting) and efferent (stimulating) nerve pathways. It also receives afferent nerves from the cerebrum and thalamus.

The basal ganglia are in contact with the cerebral cortex via functional loops. This means that information from specific areas of the cortex are interconnected with the corresponding parts of the basal ganglia and have a backward effect on them through outgoing efferent nerve pathways.

There is, for example, a functional loop which specifically acts on the muscles of the mouth and face, another one which controls the motor skills of the eyes. In addition, there are more complex loops that are related to cognitive performance, motivation, and inner drive. This is why disorders of the basal ganglia exhibit not only motor-related symptoms but also mental motivational and dementia changes.

Cerebral Cortex and Motor Control

**Function:** After a motivation for movement has arisen and a concept for the movement has been developed (both in the cerebral cortex), the concept is sent to the cerebellum and the basal ganglia. The programs for fast movements are developed in the basal ganglia and the slow ones in the cerebellum. Through the ‘gateway to consciousness’ (the thalamus), the motor programs arrive at the motor cortex, which initiates the movement.

**The motor cortex**

**Function:** Executing of complex movements

According to Brodmann, the cerebral cortex consists of different areas, with area 4 (primary motor cortex) and 6 (secondary motor cortex) forming the motor cortex. In each of these 2 areas, the muscle groups are represented somatotopically.

The motor cortex is the highest functional level in the hierarchy of motor control. It receives information from subordinated regions of the brain, processes them, and acts as a ‘general’ giving the ultimate command to execute a movement. The following precedes the execution of movement:

1. The motivation for movement originates in the limbic system and the frontal lobe.
2. Associative areas of the cerebral cortex form a concept for movement.
3. The cerebellum and the basal ganglia create the corresponding motor program.
4. The motor program travels through the thalamus to the motor cortex.

The motor cortex arranges the execution of movement via the pyramidal tract (corticospinal tract). It is connected to all the important centers of the brain; for example, to the brain stem for coordination of the supporting motor skills through the corticorubral and corticoreticular tract. From the brain stem, the rubrospinal and the reticulospinal tracts lead to the spinal cord.

The pyramidal tract has over 1 million efferent fibers, which branch on their way. One portion branches towards the thalamus, red nucleus, etc., while another portion branches towards the motor nuclei of the brain via the corticobulbar tract. The major part, however, goes directly to the motor neurons of the spinal cord. Eighty percent of these fibers cross in the lower area of the brain stem and the minor part in the spinal cord to the opposite side.
Distinction: Pyramidal tract and extrapyramidal tracts

While the pyramidal tract with its neurons in the cerebral cortex controls our conscious movements, the extrapyramidal system has its areas of nuclei below the cerebral cortex and modifies involuntary movements. It autonomously controls involuntary muscle movements and the basic muscle tone. Its connections to the visual system, the organ of equilibrium, the cerebrum, and the cerebellum enable us to smoothly execute complex movements.
Pathophysiology of the Motor Systems

Diseases of the spinal cord

Paraplegia

A complete section of the spinal cord caudally to the lesion leads to a loss of all motor, sensory, and vegetative functions. Furthermore, an initial so-called spinal shock is common. It manifests as total areflexia, which however regresses later.

Diseases of the brain stem

Decerebration syndrome

Heavy trauma to the brain can damage the tracts between the cerebral cortex and the brain stem. The cerebral cortex is consequently excluded from control (syndrome of decerebration), whereas, the function of the brain stem is preserved.

Interruption of the tracts caudal to the red nucleus leads to decerebrate rigidity (tone increase) of the extensor muscles because the inhibiting function of the red nucleus on the extensors is no longer effective, and therefore the stimulating function of the lateral vestibular nucleus predominate. Lesions below the lateral vestibular nucleus, however, do not lead to decerebrate rigidity because in this case, the activation of the extensors through the lateral vestibular nucleus has also been eliminated.

Diseases of the Cerebellum

Damage to the cerebellum (for example as a result of chronic alcohol abuse) leads to disruptions in the fine movements and coordination.

The following symptoms are characteristic:

- Hypotonus of the muscles: in case of damage in the area of the hemispheres
- Hypertonus of the muscles: in case of isolated damage of the cerebellar vermis
- Nystagmus (disruption of eye coordination) in case of damage of the medial parts of the cerebellum
- Scanned language: stagnating flow of speech
- Intention tremor (strong tremor of the extremities during voluntary movements) in case if hemisphere damage.

Asynergia:

- Disruption of target-directed motor skills (finger-nose test) = dysmetria: in case of damage of the hemispheres
- Insecure straddle gait = ataxia: in case of damage to medial parts of the cerebellum
- Inability to perform fast antagonistic movements = dysdiadochokinesia: in case of damage of the hemispheres

Diseases of the basal ganglia (Extrapyramidal movement disorders)

Lesions in the area of the basal ganglia lead to disruptions of harmonic movements.
### ‘Hyper’ symptoms

- Rigidity
- Tremor
- Ballism
- Athetosis
- Chorea

### ‘Hypo’ symptoms

- Akinesia/hypokinesia

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### Diseases with hypokinetic-hypertonic symptoms:

**Parkinson’s disease**

Parkinson’s is a degenerative disease of the substantia nigra that involves the loss of dopamine-producing cells. Because of the loss of dopamine and the resulting excess of choline, disruptions in movement modulation can occur – characterized by the symptom triad: ‘cogwheel’ rigidity, tremor, and akinesia.

**Diseases with hyperkinetic-hypotonic symptoms:**

**Huntington’s disease**

The loss of GABA and choline-producing cells in the striatum leads to a predominance of impulses triggered by dopamine. The symptoms can be tics in the form of muscle twitching, changing of the psyche, and even dementia. The movements of patients with Huntington’s disease are fast and not rhythmical and they increase in case of excitement or intending movement.

**Athetosis**

Athetosis is characterized by slow, stereotypical, vermicular movements of the extremities, which can result in abnormal joint positions.

**Ballism**

This movement disorder manifests in the case of malfunctioning of the subthalamic nucleus. It is a fast, skidding movement with sudden onset.

### Diseases of the motor cortex

**Apoplexy = Stroke**

Paralysis could result from lesions of the corticospinal tract (pyramidal tract) in the area of the internal capsule due to, e.g., bleeding. During the acute stage, loose paralysis of the contralateral side of the body is common, which turns into spastic paralysis and is characterized by pathological reflexes.

The pyramidal fibers in the internal capsule are arranged topographically, and therefore, depending on the position of damage, different muscle groups can be affected by the paralysis (hemiplegia of the arms or legs). As the motor neurons remain intact, there is no atrophy of the muscles. Fine motor skills are impaired and muscle strength is reduced because the internal capsule also conducts fibers to the brain stem and cerebellum.

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