

PART 1

# Anatomy and Physiology

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## Anatomy of the Nervous System

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This chapter's objective is not to describe the nervous system in detail, which would be impossible to do in just a few pages, but rather to provide readers who are interested in Brain–Computer Interfaces but who are not experts in anatomy, with some basics of neuroanatomy and functional anatomy as well as the vocabulary used to talk about them. Readers looking for greater depth and precision in the description of anatomical structures may consult reference books in neuroanatomy (we can cite for their clarity and exhaustiveness [KAM 13, CHE 98, DUU 98])

This description seeks to provide a general understanding of the structure of the adult nervous system, its main constituents and their principal functions, and to thereby better understand the pathologies associated with it.

This chapter will first provide a general description of the nervous system, and it will then focus on a description of the central nervous system (CNS), as well as that of the peripheral nervous system (PNS). In the last section, we will succinctly describe the main pathologies that can be addressed through the use of Brain–Computer Interfaces.



## 1.1. General description of the nervous system

A neuron is composed of a cell body and an axon, which terminates in a synaptic area. The information that travels through it is an electric signal that corresponds to a depolarization of the axonal membrane: the action potential. In this way, the axon transmits the action potential up to the synapse, the area of communication between neurons. Molecules emitted at the synapses under the influence of action potentials are called neurotransmitters. These neurotransmitters may either be excitatory or inhibitory and thus determine the response obtained.

Neurons are organized in pathways, tracts or networks whose connections determine their roles. Traditionally, a distinction is made between the CNS and the PNS. It is common to talk about efferent neurons, which transmit information from the CNS to the PNS, and afferent neurons, which transmit information from the PNS to the CNS.

The CNS includes the encephalon, which is enclosed in the skull, and the spinal cord in the spinal canal. The encephalon is itself composed of the brain stem, the cerebellum and the two hemispheres of the brain. The brain stem, located in the most caudal part of the encephalon, gives way to 12 pairs of nerves that are known as cranial nerves. The cerebellum is located in the back of the brain stem. Each hemisphere is composed of several lobes (frontal, parietal, temporal, occipital and the insular cortex). From a functional perspective, each hemisphere has its own specific functions, especially for the most complex functions (for example language in the frontal and temporal areas of the dominant hemisphere, spatial orientation in the right parietal lobe, the organization of complex gestures in frontal lobe, etc.).

The cortex, which is located on the surface of the hemispheres, is composed of gray matter that contains neuron cell bodies and is organized into six layers. The basal ganglia are located at the base of the hemispheres. These are also composed of gray matter. White matter contains myelinated axons from CNS neurons and it makes it possible to establish connections between different parts of the CNS through associative fibers (connecting parts of the cortex to each other or to the basal ganglia) and through fibers that stretch out toward the spinal cord.

The spinal cord, which contains ascending fibers and descending fibers, transmits all motor, sensitive and vegetative information between the

encephalon and the PNS. It is also composed of gray matter and is the regulation center for a certain number of reflex actions.

The roots that give way to the PNS arise from the spinal cord. These roots form, passing through the (brachial and lumbosacral) plexuses, the entire set of nerve trunks that make it possible to innervate the skeletal muscles (efferent motor fibers) to transmit sensory (sensitive afferent fibers) and vegetative (efferent and afferent vegetative fibers) information.

Different systems (motor, somatosensory, sensory) may have either ascending or descending pathways, going from the peripheral receptor to the area of the brain involved in interpreting the signal, or going from the cortex all the way to the effector (for example the muscle). We may cite, for example, the descending motor tracts distributed in a (corticospinal and corticobulbar) pyramidal pathway, which is the pathway for voluntary motion. We may also cite extrapyramidal pathways, which include other motor pathways. Other pathways include sensitive, visual, auditory, vestibular and olfactory tracts.

## 1.2. The central nervous system

The CNS includes the encephalon, which is located in the skull, and the spinal cord, which is located in the spinal canal.



**Figure 1.1.** *General view of the human encephalon*  
(<http://lecerveau.mcgill.ca>)

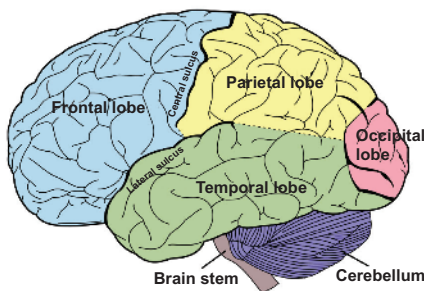
The encephalon (Figure 1.1) is usually composed of the following structures:

- the telencephalon;
- the diencephalon;
- the brain stem itself comprising the midbrain, the pons and the medulla oblongata. The cerebellum is located in the back of the pons, which is connected to the pons through the cerebellar peduncle.

It is also possible to describe the encephalon from its formation at the embryonic stage. In such a case, we can distinguish between the hindbrain, which will become the medulla oblongata and the metencephalon (pons and cerebellum), the midbrain and the prosencephalon, which will turn into the diencephalon and the telencephalon.

### 1.2.1. *The telencephalon*

The cerebrum is composed of two hemispheres (right and left) that are connected to one another through white matter tracts (especially by the corpus callosum). The surface of each hemisphere has a folded aspect, which makes it possible to individualize the lobes (Figure 1.2): the frontal lobe, the parietal lobe, the occipital lobe and the temporal lobe on the surface, and the insular lobe on the inside. These lobes are separated by sulci: the central sulcus (also known as the fissure of Rolando), the lateral sulcus or Sylvian fissure, the parietooccipital sulcus and the temporal-occipital sulcus.



**Figure 1.2.** *General view of the cortex's surface, main lobes and sulci*

The surface of each lobe itself includes several convolutions, which are known as gyri, and which make it possible to individualize the most superficial parts of the cortex. Despite variations of this structure among different individuals, it is possible to individualize sulci, fissures and gyri in most subjects with relative constancy either in morphological or functional terms.

Korbinian Brodmann, an early 20th Century neurologist and neuropsychologist, established a map of the cerebral cortex by describing 52 areas based on the tissue and histological composition of the cortex (cytoarchitectonic analysis). These are known as Brodmann areas. Brodmann attributed a specific function to each of them. Some of those areas are now subdivided into subareas, and that mapping is still used today [GAR 06].

The functional role of the different areas of the cerebral cortex is traditionally described in the following manner:

- the primary areas, which include the primary motor cortex, and areas that receive sensory stimuli: primary somatosensory cortex (parietal lobe) for sensory information, primary auditory cortex (temporal lobe) and primary visual lobe (occipital lobe);

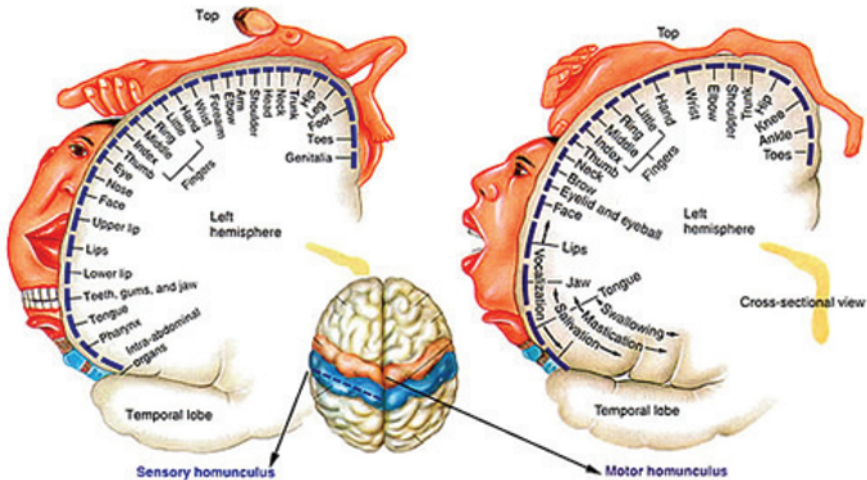
- the secondary areas, which correspond to elaborate information processing that may be plurimodal, and associative areas, whose functions are more amodal (cognitive and attentional functions) and that most notably make it possible to pay attention to stimuli to identify them. Cognitive functions are processed in such areas.

Let us now review the different lobes:

- *The frontal lobe*: The frontal lobe is composed of the precentral gyrus, the premotor areas and the prefrontal areas. In the dominant hemisphere, it contains Broca's area, which is considered the area of speech production. It is delimited by the central sulcus, which separates it from the parietal lobe, and by the lateral sulcus, which separates it from the temporal lobe.

The primary somatomotor cortex (Brodmann area 4, often called M1), which is located on the precentral gyrus, controls voluntary motor activity. Its efferent fibers form the main part of the pyramidal tract, responsible for direct motion. To every point on the precentral gyrus corresponds a part of the body

that it controls: this is called functional somatotopy. To illustrate this, a map known as the cortical homunculus has been created [PEN 50] (Figure 1.3).



**Figure 1.3.** Representation of the motor and sensory homunculi (<http://www.corpshuman.ca>)

A lesion in this area can lead to a large or small contralateral paralysis, which corresponds to the projection described in the motor homunculus (hemiparesis).

The prefrontal cortex plays an essential role in determining behavior, motivation and organizational planning, and decision execution capacities. Especially developed in humans, the prefrontal cortex plays an important role in thought elaboration and personality development. Along with the basal ganglia, it is involved in complex motor learning and contributes to long-term memory. In neuropsychology, it is common to speak of executive functions, which include all so-called higher level cognitive functions. Damage to the prefrontal cortex can bring about motor skills learning disorders (for complex tasks), as well as behavioral disorders (lack of initiative, disinhibition, difficulty in planning simple or complex tasks, etc.).

The premotor cortex (which includes the lateral premotor cortex on the outer layer of the frontal lobe, and the supplementary motor area on the midline surface of the hemispheres) is located just anterior to the primary motor cortex.



It is the site of movement planning and organization tasks. Several association fibers connect it to the motor cortex, the cerebellum, the thalamus and the basal ganglia. It makes it possible to select the appropriate movements needed to carry out a desired action. A lesion in the premotor cortex can compromise the capacity to carry out movement toward a specific goal. This is known in clinical terms as dyspraxia.

Broca's area is the area that controls speech production. An injury in Broca's area, which is most often located on the surface of the left hemisphere, can lead to an expressive aphasia. Patients retain the capacity to understand language, but they omit words or employ non-grammatical syntax when attempting to express themselves.

– *The parietal lobe*: the parietal lobe is located between the central sulcus, the lateral sulcus and the parietooccipital sulcus. It comprises the postcentral gyrus, the superior parietal lobule and the inferior parietal lobule.

The primary somatosensory cortex is located in the postcentral gyrus. It receives sensory information and makes it possible to interpret it (as pain, temperature, touch, discrimination, vibration, relative joint positions, etc.). Similarly to the motor homunculus, the organization of the primary motor cortex gives rise to a sensory homunculus (Figure 1.3, left).

An injury in the parietal lobe can produce several different disorders: attentional disorders such as hemispatial neglect (especially in the left hemisphere), sensory extinction, body image disorders and spatial agnosia.

– *The temporal lobe*: the temporal lobe is located in the lower face of the cerebrum and is bounded by the lateral sulcus and the preoccipital notch, which is poorly defined in anatomical terms. From an architectonic standpoint, it is composed of the transverse temporal gyrus (primary auditory cortex), the associative auditory cortex (including Wernicke's area) and the associative temporal cortex involved in language memory. The information coming from each auditory nerve is bilaterally projected in the the primary auditory cortices, for which it is possible to describe a tonotopy (activated areas are associated with a specific sound frequency).

An injury to the temporal lobe can bring about auditory disorders (cortical deafness, auditory agnosia, auditory hallucinations, transcortical sensory aphasia if the dominant hemisphere is injured, quadrantanopia).

– *The occipital lobe*: as previously described, the occipital lobe is separated from the parietal lobe by the occipitoparietal sulcus and from the temporal lobe by the preoccipital notch, although less markedly so.

It is divided into three occipital gyri: the cuneus, which is separated from the lingual gyrus by the anterior calcarine sulcus and the occipitotemporal gyrus, which is separated from the lingual gyrus by the collateral sulcus.

The primary visual cortex (V1) and the associative visual cortex are located at the level of the occipital lobe. Much like for the primary motor cortex, or the primary somatosensory cortex, there is a systematic correspondence, with every point in our visual field being represented in a specific area of V1. This property relating V1 to the retina is known as retinotopy.

– *The insular cortex or lobe*: the insular cortex is the “5th lobe” in our brain. It is located deep within the frontal, parietal and temporal opercula. Although it is less precisely understood, we know that the insular cortex is involved in corporal self-consciousness, in pain intensity recognition and, for example, in the perception of heartbeat frequency.

### **1.2.2. The diencephalon**

This is the part of the brain that connects the brain stem to the cerebral hemispheres. It bounds the third ventricle on both sides. The diencephalon is composed of the thalamus, the hypothalamus (center of the vegetative nervous system), the subthalamus, the epithalamus and the basal ganglia. It is bounded on the side by the internal capsule.

The thalamus is a set of ganglia that receive a variety of afferents. It is the true relay center of sensory, motor and emotional information for the cerebral cortex. It is divided by the medullary laminae into medial, lateral, anterior and posterior nuclei. Each area is a specific anatomical relay that determines its functions.

The thalamus is in part controlled by thalamic reticular formation, a set of neurons that separate it from the internal capsule, determining the state of cortical activity.

The thalamus is involved in the transmission of visual, auditory, somatosensory and vestibular information. It plays a role in awareness of

transmitted pulses (perception of pain or heat, and of emotional perception) and contributes to the execution of movement.

It receives several afferents (hypothalamus, mammillary body, basal ganglia, sensory afferents, cerebellum, etc.) and it emits several efferents (prefrontal cortex, cingulate gyrus, associative parietal cortex, pallidum, auditory and visual cortex, motor cortex, etc.). It is in this sense a true circuit board for all information processed and transmitted by the nervous system.

The hypothalamus, which is the center of all vegetative functions, is divided into anterior, tuberal and posterior regions. It is located above the thalamus and is connected to the pituitary gland by the pituitary stalk. Because of its multiple connections, it can control the vegetative system (through the sympathetic and parasympathetic nervous systems). It can also regulate homeostasis (maintaining constant internal conditions, including temperature and electrolyte equilibrium). The hypothalamus is also involved in food intake and cardiac cycle regulation.

The pituitary gland plays a role in endocrine function regulation. The epithalamus contains the epiphysis, an endocrine gland that produces melatonin and contributes to sleep cycle and circadian cycle regulation.

The basal ganglia are part of the extrapyramidal system, and include the putamen, the caudate nucleus and the globus pallidus. The putamen and the caudate nucleus form the neostriatum, while the globus pallidus and the putamen form the lenticular nucleus.

The striatum receives not only a large amount of information coming from motor brain areas, but also from the temporal, parietal and limbic areas. It plays a major role in the execution of voluntary movement carried out in a regular and fluent manner, as well as in determining behavioral and cognitive functions. The striatum is, among others, connected to the thalamus and to the substantia nigra (located in the midbrain) and is also involved in involuntary movement control.

From an anatomical standpoint, the caudate nucleus receives information from association areas and from motor areas of the frontal lobe, which most prominently allow for control of complex movements.

The putamen receives information coming from the primary and secondary somatosensory areas of the parietal lobe, the secondary visual areas, the associative auditory areas of the temporal lobe and the frontal lobe's motor and premotor cortices. Its neurons are activated when a given movement is about to occur. The striatum is an indispensable element in movement activation.

Within the basal ganglia, it is common to talk about the subthalamic nucleus, also known as corpus Luysi or Luys' body. This anatomical structure is particularly interesting in the scope of clinical practice because the neurosurgical implantation of stimulation electrodes in this site is an effective treatment for Parkinson's disease.

The substantia nigra, located further down in the midbrain, is also traditionally considered a part of the basal ganglia.

### 1.2.3. The brain stem

The brain stem is composed of the midbrain, the pons and the medulla oblongata (Figure 1.4). It is located at the back of the cerebral hemispheres and extends as far back as the foramen magnum. The nuclei of the cranial nerves emanate from the gray matter of the brain stem at different levels. The (I) olfactory and (II) optic nerves are expansions of the CNS. All ascendant and descendant pathways (pyramid, spinothalamic tract, posterior column, medial lemniscus pathway, etc.) pass through the brain stem.

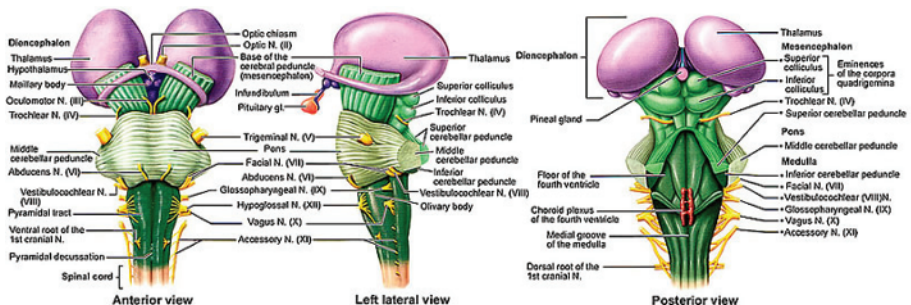


Figure 1.4. Brain stem, anterior, lateral and front views (<http://www.corpshuman.ca/>)

The midbrain connects the diencephalon to the pons. It gives way to the (III) oculomotor and (IV) trochlear nerves, which contribute to oculomotricity. Among others, the nuclei of the substantia nigra, red nuclei (extrapyramidal system) and the reticular formation are found in the midbrain.

The pons (also called pons Varolii) connects the midbrain to the medulla oblongata and is itself connected to the cerebellum through the cerebellar peduncles, which are crossed by the trigeminal nerve (V, transmitting sensation in the face, a part of the tongue and muscles responsible for mastication). The trochlear (VI, involved in oculomotricity with III and IV), facial (VII, whose main function is face and muscle movement) and vestibulocochlear (VIII, hearing and balance organs) nerves arise from it.

Finally, the medulla oblongata or bulb extends from the pons all the way to the first cervical nerves. On the ventral part, we find the corticospinal fibers (pyramidal pathways). This is the anatomical site of the intersection or decussation of those fibers, which is responsible for the left side of the brain controlling the right side of the body and vice versa.

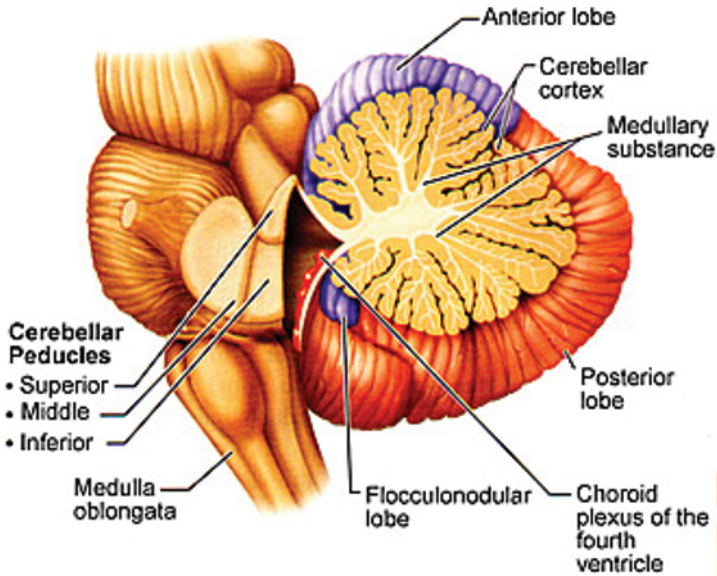
From the medulla oblongata arise the glossopharyngeal nerves (IX) and the vagus nerve (X) (IX and X are involved in the oropharynx's locomotion and sensory capacities, which are responsible for swallowing and phonation), as well as the accessory nerve (XI, motor innervation for some muscles in the cephalic region) and the hypoglossal nerve (XII, tongue motor innervation).

The brain stem contains centers included in the autonomic nervous system (ANS). In this way, the parasympathetic nervous system's efferents originate at the brain stem at nuclei III, VII, IX and X of the cranial pairs. It is a cholinergic system that is controlled by the hypothalamus (superior vegetative nervous system) described above. This system controls the functions of several organs (the iris, lacrimal and salivary glands, the heart, lungs, stomach, pancreas, intestinal smooth muscle tissue and digestive glands), and thus confers a vital function to the brain stem.

The brain stem is the site of several reflexive and vital activities.

### 1.3. The cerebellum

The cerebellum, which is shown in Figure 1.5, is a fundamental part of the CNS, as the major coordination center for equilibrium and muscle tone. It enables the completion of specific motor tasks.



**Figure 1.5.** *Brain stem and cerebellum* (<http://www.corpshumain.ca>), lateral view

At the anatomical level, it is composed of two lateral hemispheres (right and left) and the cerebellar vermis in the medial zone. It is connected to the dorsal side of the brain stem by three pairs of cerebellar peduncles and is covered by the tentorium cerebelli, which separates it from the cerebral hemispheres. It is divided into ventral, superior and inferior faces. It receives inflows coming from the cerebral cortex, the brain stem and the medulla oblongata, thus constituting several afferent and efferent connections.

From a functional perspective, the cerebellum is divided into three parts determined by their phylogenetic origin: the neocerebellum, the paleocerebellum and the archicerebellum.

The neocerebellum is composed of two cerebellar hemispheres. It is the largest of the three parts. It receives information coming from the cerebral cortex through the corticopontocerebellar pathway, and information coming from the oliva through the olivopontocerebellar pathway.

The neocerebellum is the fundamental element that makes it possible to carry out voluntary and involuntary movement in a precise manner. An injury to this part of the brain would cause motor disorders, affecting coordination in particular.

The paleocerebellum is composed of the ventral part of the cerebellum. It receives information from the spinal cord through the dorsal and ventral spinocerebellar tracts, as well as the cuneocerebellar tract. Its role is very important in the maintenance of equilibrium and involves contributing to muscular tone and agonistic–antagonistic muscle synergy regulation. An injury to this structure leads to hypotonia.

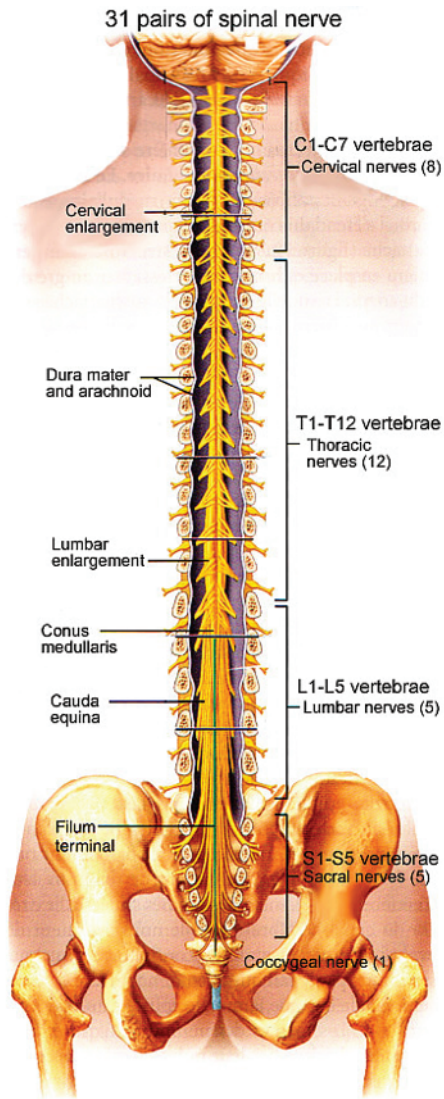
The archicerebellum is composed of the nodulus and the flocculus. It is connected to the vestibular system and receives information about the head's position in space during movement. It makes it possible to maintain equilibrium and to have appropriate ocular and cephalic reactions to movement. When injured, patients present a so-called ataxic walk (stumbling, with an enlarged support polygon).

#### **1.4. The spinal cord and its roots**

The spinal cord is the part of the CNS that goes from the foramen magnum to the skull base, advancing through the spinal canal formed by the vertebrae up until dorsal vertebra L2.

It forms a cylinder with a diameter of approximately one-third of an inch and a length of 15–18 inches in adults (Figure 1.6). Spinal nerves stem from the vertebral column at different heights (eight cervical spinal nerves, labeled C1–C8; 12 thoracic nerves, labeled T1–T12, five lumbar nerves L1–L5, five sacral nerves S1–S5 and one coccygeal nerve).

The roots exit the spinal canal through foramina located between two vertebrae. The whole cord is covered by the meninges membranes (dura mater, arachnoid mater, pia mater) and immersed in cerebrospinal fluid.



**Figure 1.6.** *Spinal cord and spinal nerves, general view*  
(<http://www.corpshuman.ca>)



During development, growth in the size of the spinal canal is more important than growth of the spinal cord, which is why the lower end of the spinal cord (called conus medullaris) is usually found at L2 in adults. The cauda equina designates the set of nerve roots located between the conus medullaris and the last vertebra.

There are two regions where the spinal cord enlarges, one at the cervical level and another at the lumbar level, and they serve to innervate the upper and lower limbs.

The spinal cord has vegetative fibers and is the center of reflexive motor activity that has the purpose of regulating muscle tone. Surrounding the spinal cord is white matter containing all ascending and descending fibers that transport sensory afferent messages and efferent motor messages. At the center of the spinal cord, there is gray matter, which contains neuronal nuclei.

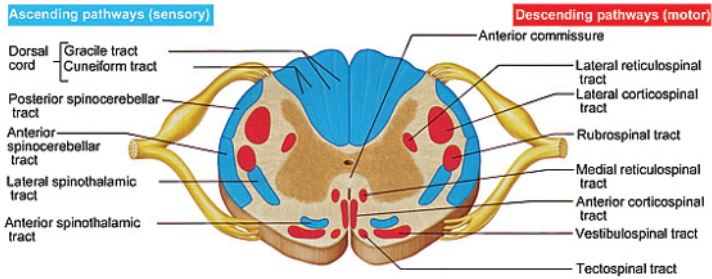
From an anatomical point of view, it is possible to describe three white matter cords in each half of the spinal cord (Figure 1.7), which contains ascending and descending pathways:

- the posterior cord (cuneiform tract of the upper limb and gracile tract of the lower limb) contains the large diameter myelinated ascending fibers (also known as the posterior column-medial lemniscus pathway), which transmits limbs' conscious position sensibility (proprioception), tact and pressure;

- the lateral cord contains the pyramidal tract and the spinothalamic lateral tract (pain, temperature). The spinocerebellar (dorsal and ventral) tracts transmit unconscious deep sensory information (which most notably makes it possible to regulate axial muscle tone);

- The anterior cord contains ascending spinothalamic ventral fibers (sensitivity to pressure, called protopathic).

Gray matter is usually composed of the central area, the anterior gray column and the posterior gray column. The posterior gray column includes the synaptic connections for all sensory information coming from the dorsal root of the spinal nerve. The anterior gray column contains the bodies of  $\alpha$  motor neurons, and gives way to the anterior root of the spinal nerve.



**Figure 1.7.** Cross-section of the spinal cord (<http://www.corpshumain.ca>), diagrammatic representation of ascending and descending tracts

## 1.5. The peripheral nervous system

### 1.5.1. Nerves

A nerve is a collection of sensory, motor and/or vegetative axons. When it is exclusively composed of motor or sensory axons, it is called a motor or sensory nerve. When it is composed of a combination of both, it is called a mixed nerve. Its neural fibers are either myelinated or non-myelinated. Myelin is a substance that determines the speed at which nervous influx is conducted. Myelin is produced by Schwann cells.

Sensory fibers are divided into several groups according to their size:

- *Group I:* it consists of type Ia fibers (approximately  $17\mu\text{m}$ , with a conduction speed of 70–120 m/s), which are myelinated and transmit unconscious proprioceptive sensibility through neuromuscular spindles, and Ib fibers (approximately  $16\mu\text{m}$ , with a conduction speed of 70–100 m/s) based on the Golgi apparatus. They transfer information to the cortex through the spinocerebellar tract. Ia fibers also communicate with the spinal cord in the monosynaptic reflex arc;

- *Group II:*  $\alpha\beta$  and  $A\gamma$  fibers ( $8\mu\text{m}$ , 15–40 m/s) are myelinated and transmit epicritic sensitivity as well as deep sensitivity;

- *Group III:*  $\delta$  fibers ( $3\mu\text{m}$ , 5–15 m/s) are myelinated and they enable the transmission of thermal sensitivity, pain and pressure;

– *Group IV*: C fibers (0.2–1 $\mu$ m, 0.2–2 m/s) are unmyelinated and are responsible for transmission of pain and temperature, as well as coarse tactile sensations.

Motor fibers are divided into  $\alpha$  motor neurons, which innervate the striated skeletal muscles that are responsible for movement, and  $\gamma$  motor neurons, which innervate the muscular part of neural spindles, which are key in controlling muscle tone.

Vegetative fibers are described in section 1.5.3, which deals with the ANS.

Neural fibers (myelinated or unmyelinated motor/sensitive/vegetative fibers) are enclosed in a connective tissue called endoneurium. They are first bundled into nerve fascicles enclosed in perineurium, and then several fascicles are enclosed in endoneurium, giving way to a nerve.

### **1.5.2. General organization of the PNS**

The PNS is composed of the following:

– efferent motor fibers consisting of a cellular body that arises from the spinal cord's anterior gray column, an axon (which constitutes the motoneuron) and a neuromuscular junction (NMJ), where the axon and the innervated muscle interact. Motor fibers come together to form the ventral root of a spinal nerve;

– afferent sensory fibers transmit peripheral information to the CNS, whose cell body is located in the dorsal root ganglion. They communicate with the spinothalamic and spinocerebellar tracts as well as with the posterior column–medial lemniscus pathway at the level of the spinal cord's posterior horn. They transmit information from the skin, muscles, joints and organs. They form the spinal cord's dorsal root.

Dorsal and ventral roots unite at each metamerism of the spinal nerve (which is composed of motor and sensory fibers that are coupled with vegetative fibers). In total, there are 31 pairs of spinal nerves and 12 pairs of cranial nerves. Spinal nerves are each composed of a ventral and a dorsal root. These bind to the roots of other spinal nerves to form plexuses, which give way to muscular, skin and organ nerves.

We may thus distinguish between the following:

- the *cervical plexus* that is formed by the ventral roots going from C1 (first cervical root) to C4 and innervating the nape and neck muscles. The phrenic nerve (responsible for diaphragm motricity) also originates in the cervical plexus;

- the *brachial plexus* that is formed by the union of ventral fibers going from C5 to T1 (first thoracic or dorsal root). The auxiliary, musculocutaneous, radial, median and ulnar nerves (which are responsible for the upper limbs) in the brachial plexus;

- the *lumbosacral plexus* that is composed of the roots of L1 to S3. The femoral, obturator, iliohypogastric, genitofemoral, ilioinguinal and sciatic nerves, as well as the lateral cutaneous nerve of the thigh, which are responsible for sensory and motor innervation of the lower limbs, originate in the lumbosacral plexus;

- the *puddental plexus* that is formed by the S2–S4 roots coming together in the pudental nerve.

It is possible to produce a map of cutaneous areas according to their radicular innervation, known as dermatomes. Each muscle is innervated by a nerve originating in one or another of the aforementioned plexuses. One root innervates a set of muscles, which is known as a myotome.

The junction between a motor neuron axon and a muscle is called the NMJ. A motor neuron's axon splits in two to innervate a certain number of muscular fibers. The set of muscular fibers innervated by a given axon constitutes a motor unit. This system is cholinergic: an action potential leads to the release of acetylcholine within a synapse. Reception of acetylcholine by the postsynaptic nicotinic receptors of the motor endplate leads to the contraction of muscular fibers.

### **1.5.3. *The autonomic nervous system***

The peripheral vegetative or ANS works involuntarily. It is composed of the sympathetic and parasympathetic systems.

Vegetative fibers innervate the viscera, the glands and the vessels (smooth muscle). They allow for involuntary movement, and they enable the transmission of pain from the organs to the cortex.

The most important functions that are regulated by the ANS are body temperature, sweat, pilomotor functions, the cardiovascular system, breathing, the digestive system, detrusor–sphincter and genitosexual functions.

## 1.6. Some syndromes and pathologies targeted by Brain–Computer Interfaces

### 1.6.1. Motor syndromes

1) *Peripheral neuropathic syndrome*: this refers to symptoms observed when there is damage to peripheral nerves, regardless of the cause (trauma, intoxication or illness). The symptoms are either localized (injury to the nerve trunk or to a root) or diffused. Flaccid paralysis is the most common symptom, along with amyotrophy and hypotonia. There is also autonomic dysfunction (vasomotor dysfunction, problems with blood pressure regulation, diarrhea or constipation, impotence, etc.);

2) *Pyramidal syndrome*: pyramidal syndrome results from injury to the corticospinal tracts. From a clinical standpoint, it is possible to observe motor command disorders (paralysis) ranging from partial deficit to total deficit. This kind of paralysis is associated with muscle tone disorders and spasticity, which has been described as an overly augmented stretch reflex. Beyond paralysis, spasticity can have major functional consequences, which may involve muscular retractions and joint stiffness. Clinicians look out for this syndrome by studying tendon reflexes that may be overactive;

3) *Cerebellar syndrome*: cerebellar syndrome is the result of either an injury to the cerebellum itself or to one of the cerebellar pathways. Its most common symptom is cerebellar ataxia, which includes gait abnormality and orthostatic intolerance. Patients walk in a “wobbly” manner, and their support polygon is expanded. Muscle tone is diminished (hypotonia) and coordination and voluntary movements are altered. It is possible to observe, for example, dysmetria (lack of coordination in space), adiadochokinesia (lack of coordination in time) and shakiness when executing movements. Speech is also affected, which is known as cerebellar dysarthria;

4) *Extrapyramidal syndrome*: this syndrome is the product of damage to the extrapyramidal system described above. It is associated with hypertonia (called extrapyramidal hypertonia), at-rest shakiness or hypokinesia (difficulty initiating movement and decreased bodily movement). From a clinical standpoint, it is possible to observe postural disorders as well as gait abnormality (trampling or festination, anteflexion, *marche à petits pas*, absence of parachute reaction), dysarthria, micrography (which makes writing illegible) and cognitive disorders (psychic slowness, perseveration, etc.).

### **1.6.2. Some pathologies that may be treated with BCIs**

1) *Spinal cord injuries*: spinal cord injuries are most often the product of trauma. A distinction is made between instances where the damage occurs at the site of the lesion, in which case peripheral neuropathic syndrome can be observed, and instances where the damage produces a pyramidal syndrome, or sensory, vesicosphincteric and genito-sexual disorders. Clinically, it is common to describe the level of the spinal injury in terms of the lesional syndrome (last healthy metamerism).

Spinal cord injuries are divided into complete (all motor and sensory functions are affected) and incomplete injuries. Tetraplegia refers to injuries affecting all four limbs, and paraplegia refers to injuries affecting only the lower limbs.

Spinal cord injuries are classified according to the location of the affected area. For example;

- Brown–Séguard syndrome or hemiparaplegic syndrome: the spinal injury is unilateral, with paralysis on the side of the body where the lesion occurred, as well as damage to proprioception. Contralateral thermoalgie damage is observed,

- anterior compartment syndrome: motor and thermoalgie deficit without any additional sensory damage,

- posterior cord syndrome: purely sensory damage and pain is abundant; the sensory deficit concerns proprioception, but preserves thermoalgie sensation;

2) *Locked-in syndrome*: locked-in syndrome (LIS) is also known as cerebromedullospinal disconnection or de-efferented state: it is the result of an

injury to the motor pathways at the brain stem, most often on the protuberance. Voluntary limb and face movement is affected, as are deglutition, phonation and oculomotricity. Sensory and cognitive functions are usually preserved. The patient is therefore capable of perceiving his or her environment and remains perfectly conscious. The capacity to raise the eyes is often retained, making it possible for patients to communicate. One of the most important challenges when caring for patients affected with LIS is establishing effective communication.

3) *Hemiplegia*: hemiplegia is characterized by a bodily motor deficit on the opposite side of a lesion to the primary motor cortex or of the subcortical pyramidal tract. The deficit can either be total or partial (in which case it is referred to as a hemiparesis). Hemiplegia is most often the product of a cerebrovascular accident or stroke and produces other symptoms according to the affected area. Related cognitive disorders can make access to BCIs difficult for patients.

4) *Amyotrophic lateral sclerosis (ALS) also known as Lou Gehrig's disease or Charcot disease*: ALS is a form of degenerative, progressive damage to both central motor neurons and peripheral motor neurons. It is therefore associated with pyramidal syndrome and peripheral neuropathic syndrome. Patients first display distally with atrophy, fasciculations and quick reflexes, as well as spasticity. There is no sensory damage.

The disorder affects the limbs, as well as deglutition and phonation, making it difficult for patients to communicate.

## 1.7. Conclusions

It is difficult to describe neuroanatomy with any degree of precision in just a few pages. This chapter's authors hope that readers who are not already familiarized with anatomy will have understood the general structure of the nervous system and will have acquired its most important terms, thereby making it possible to understand the following chapters. The description provided here is partial by design, and has therefore left out important structures (such as the ventricular system), with an important role in pathology, but which have been deemed to fall outside the scope of this book. This being said, it is important for readers interested in a specific structure of the nervous system to consult reference works in neuroanatomy. Indeed, knowledge of neuroanatomy is necessary in order to understand how

Brain–Computer Interfaces work, and sharing common neuroanatomical knowledge is important for the fruitful collaboration of actors from different fields.

## 1.8. Bibliography

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