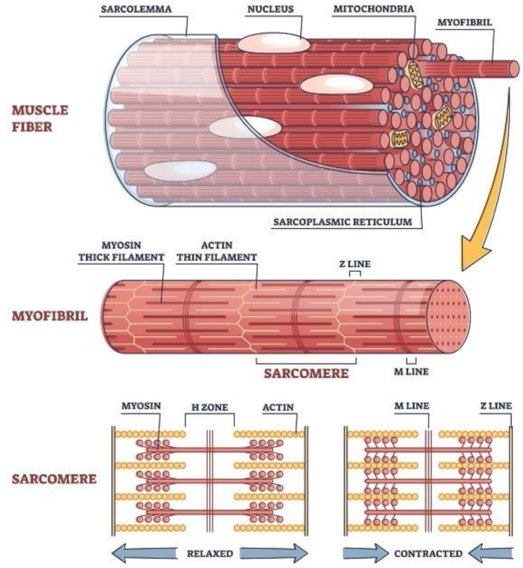
Motor System

Efferent Somatic Pathway

Movement represents the primary output system of the human body. Every activity we perform, from the beginning of life to its end, involves a motor component. In fact, there is essentially no productive human activity that does not involve movement, as it is through movement that we interact with the external environment.
If we consider activities such as walking or running, the role of movement is immediately evident; however, it is also fundamental in activities that appear to be purely cognitive. During reading, for example, the eyes perform continuous movements to scan the text; when we speak, we engage in a highly refined coordination of the tongue, facial muscles, and masticatory muscles to articulate words; during writing or computer work, we move our hands to produce content. Therefore, movement is not limited to locomotion but represents an essential component of all human functions, serving as the means through which we generate any output toward the external world.

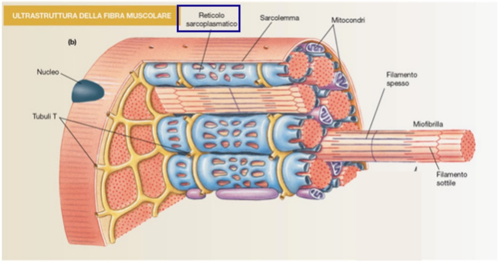
The motor system can be divided into two main components:
Somatic motor system, which controls voluntary muscle activity
Autonomic nervous system, which controls involuntary muscle activity

Structure of Skeletal Muscle



Skeletal muscle fibers are true **syncytia** because they derive from the fusion of multiple cells (myoblasts), so they contain many nuclei within a single cytoplasm.

Muscle tissue is made up of muscle fibers, and the simplest functional unit is the **sarcomere**.



How do we move? We move using muscles.
But what is a muscle?
Skeletal muscle fibers are true syncytia because they are formed by the fusion of multiple cells (myoblasts), so they contain many nuclei within a single cytoplasm.
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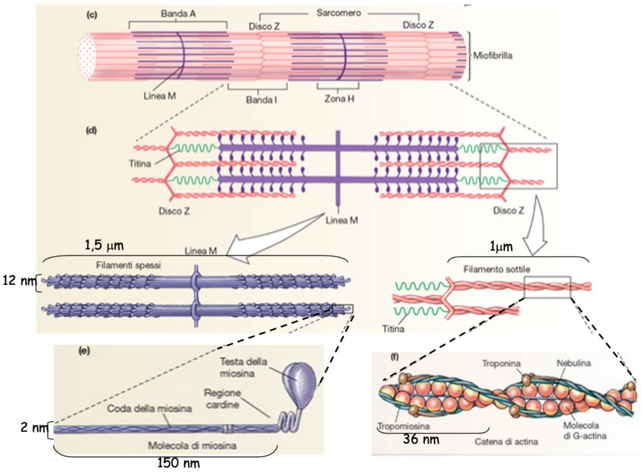
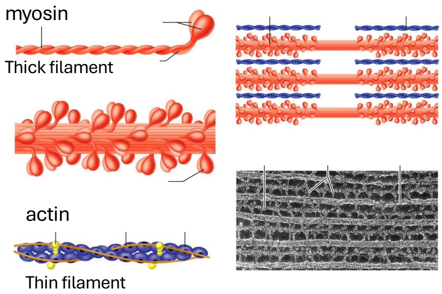
The sarcomere



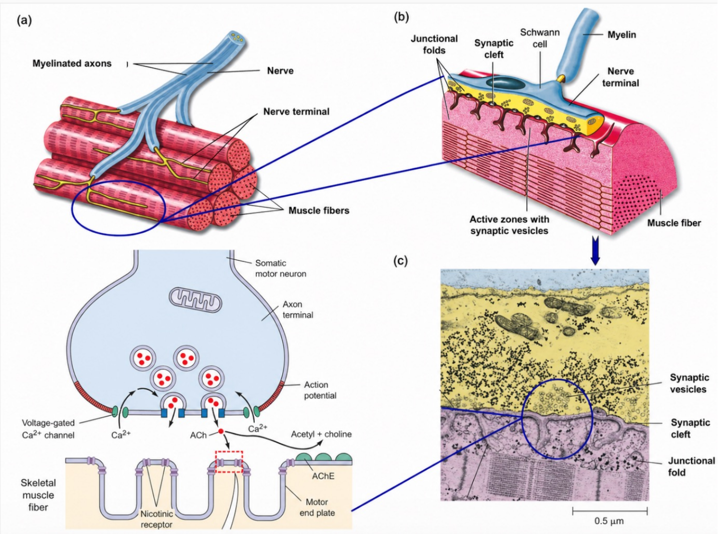


THE UNIT RESPONSIBLE FOR MUSCLE CONTRACTION

Actin and **myosin** are contractile proteins
Tropomyosin and **troponin** are regulatory proteins
Titin and **nebulin** are structural proteins

The sarcomere, the unit responsible for muscle contraction, is made of structural and regulatory proteins (see slide).
Actin → thin filament
Myosin → thick filament
Tropomyosin→ regulatory protein
Troponin→ regolatory protein
Titin→ structural protein
Nebulin→ structurale protein

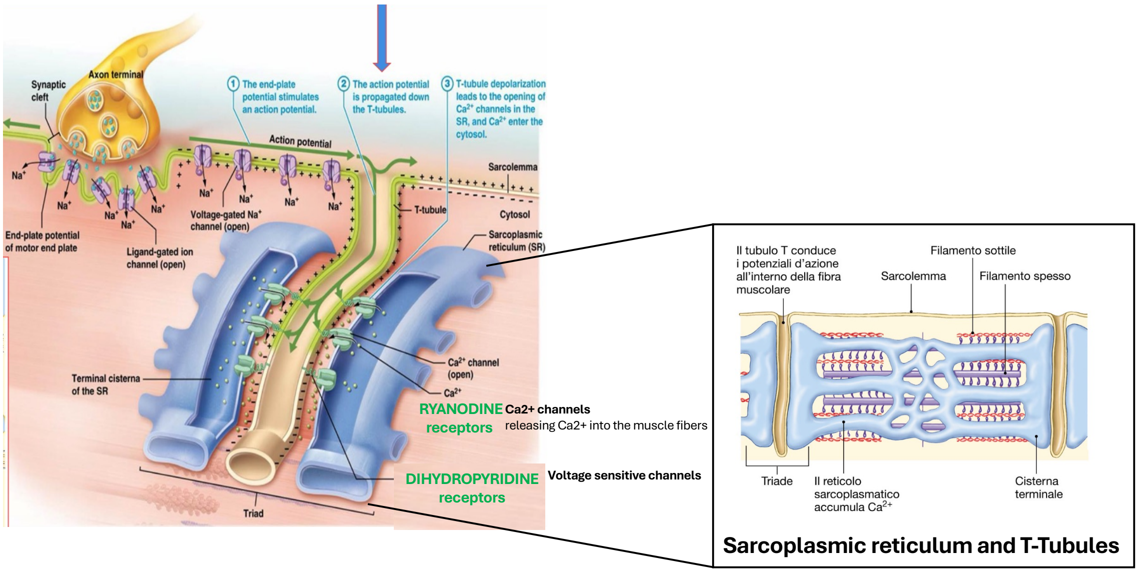
Neuromuscolar Juction



However, the muscle does not contract by itself.
It contracts thanks to an electrical signal provided by neurons.
The neuron connects to the muscle through the **neuromuscular junction**.
The connection between a neuron (motor neuron) and the muscle fibers forms a **motor unit**.
A motor neuron can innervate multiple muscle fibers through multiple junctions, making contact with invaginations of the sarcolemma (the muscle cell membrane).
At the contact between neuron and muscle, a neurotransmitter called **acetylcholine (ACh)** is released.
The neuron releases ACh →
ACh binds to receptors on the muscle fiber membrane (sarcolemma) →
These receptors are ligand-gated ion channels → Na^+ enters →
This creates a local depolarization (**end-plate potential**).

Curiosity:
Lidocaine, like similar drugs, is a local anesthetic used for example in dental procedures to reduce pain.
It works by blocking voltage-gated Na^+ channels.
Lidocaine enters the cell because it is lipophilic and then binds inside the channel, preventing Na^+ from entering.

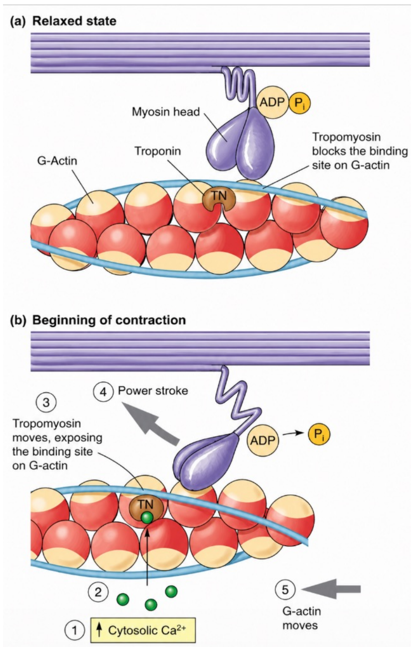
T-tubules
which are invaginations of the sarcolemma that
carry the electrical signal deep into the muscle fiber.



Sarcoplasmic reticulum and T-Tubules

If the depolarization is strong enough:
voltage-gated sodium channels open → an action potential is generated and spreads along the entire membrane.
The signal reaches the **T-tubules**, which are invaginations of the sarcolemma (muscle cell membrane) that carry the electrical signal deep into the muscle fiber.
Inside the T-tubules there are **DHPR receptors** (dihydropyridine receptors), which are voltage-sensitive.
These are physically connected to **ryanodine receptors (RyR)** on the sarcoplasmic reticulum.
RyR are calcium channels, and when activated by DHPR, they cause the release of **Ca^{2+}** into the muscle fiber.

Ca2$^+$ activates the contraction



On actin there are also two **regulatory proteins**:

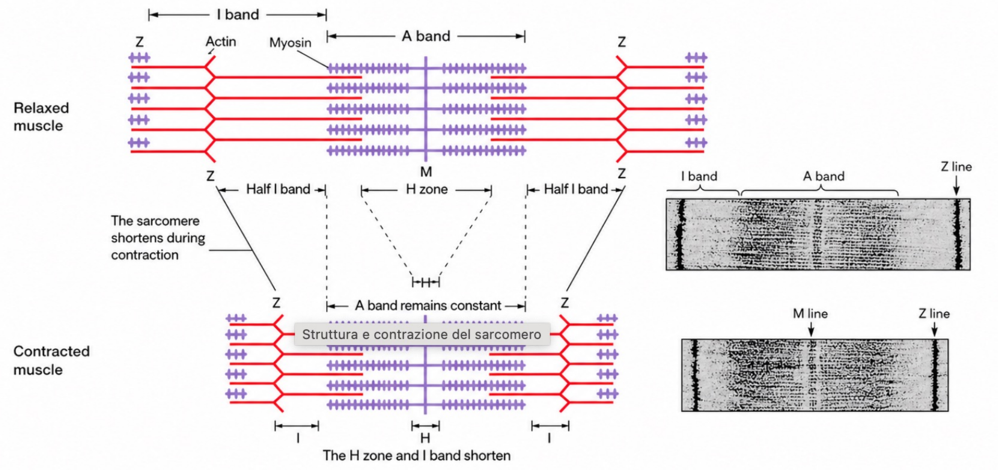
Tropomyosin → at rest, it covers the binding sites on actin and prevents myosin from binding

Troponin → binds Ca^{2+} and, when it does, it moves tropomyosin

In this way, the binding sites on actin become accessible. Myosin binds to actin and, using ATP, pulls it toward the center of the sarcomere.

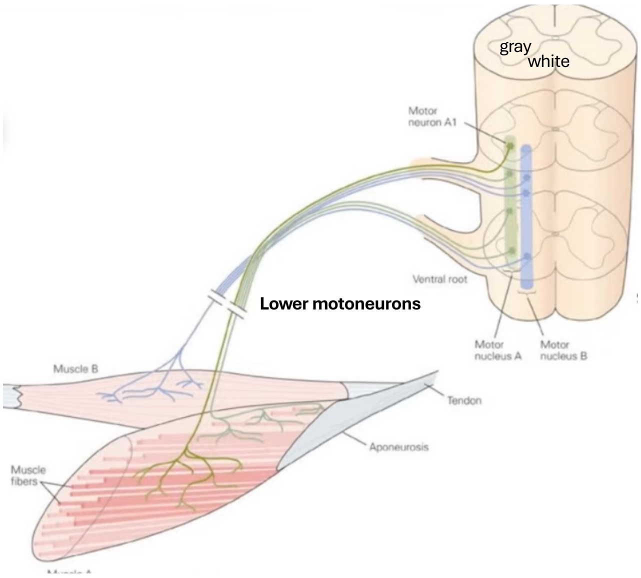
This causes sliding of the filaments and shortening of the sarcomere (**MUSCLE CONTRACTION**).

Muscle contraction occurs through the sliding of filaments



- The length of the A band remains constant during contraction (Huxley and Niedergerke, 1954).
- Myosin and actin filaments do not change in length, but the degree of overlap between them varies with the length of the sarcomere.
- **Sliding filament theory:** during contraction, the shortening of the sarcomere occurs as a result of the active sliding of thin filaments (actin) over thick filaments (myosin).

The spinal cord

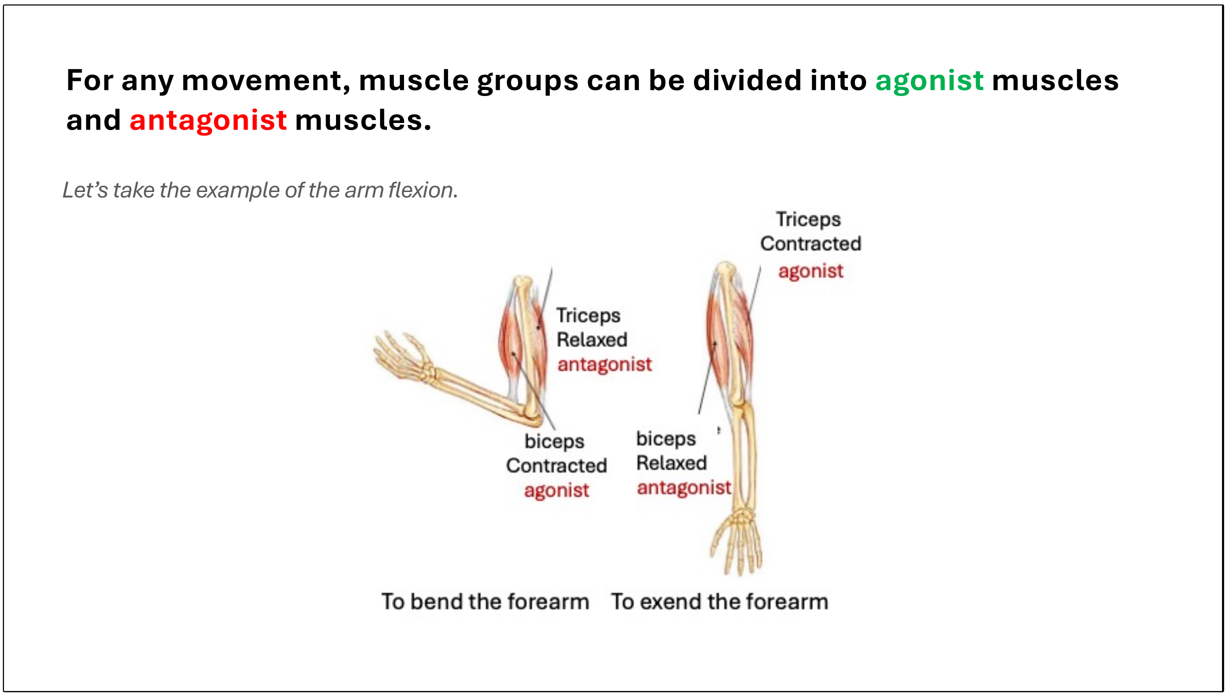


Motor neurons control muscle contraction at the level of the spinal cord. The spinal cord is a tubular structure of the central nervous system, relatively compact and well protected by the vertebral column.

From an anatomical perspective, it exhibits a characteristic internal organization: **white matter** is located peripherally, while **gray matter** occupies the central region, forming a typical “H” (or butterfly) shape.

Within the **anterior horns** of the gray matter are located the cell bodies of somatic motor neurons. These neurons, known as **lower motor neurons**, represent the final common pathway of the motor system, as their axons directly innervate skeletal muscle fibers. Signal transmission occurs at the **neuromuscular junction**, leading to muscle contraction.

The spinal cord also receives descending inputs from higher centers, particularly from the cerebral cortex and other brain structures. These inputs modulate the activity of lower motor neurons, allowing for the execution and control of voluntary movement.



For any movement, muscle groups can be divided into agonist muscles and antagonist muscles.

Let's take the example of the arm flexion.

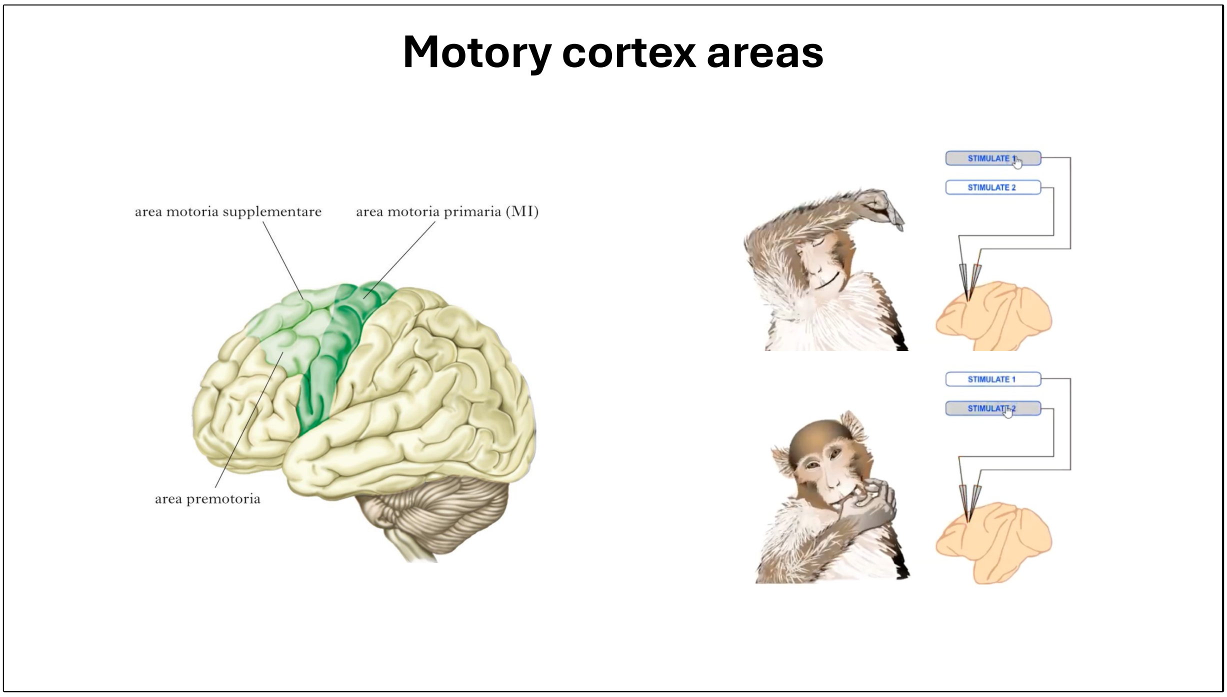
To bend the forearm To exend the forearm

For any movement, muscle groups can be classified into **agonist muscles** and **antagonist muscles**.
Let us consider the example of the arm. Starting from an extended position, flexion of the forearm does not simply require contraction of the biceps. The arm contains both the **biceps brachii** and the **triceps brachii**. To produce flexion of the forearm at the elbow joint, it is necessary to contract the biceps while simultaneously relaxing the triceps. If the triceps remained contracted, flexion would not be possible.
Conversely, during extension of the forearm, contraction of the triceps must be accompanied by relaxation of the biceps.
The **agonist muscle** is the muscle primarily responsible for generating a specific movement, whereas the **antagonist muscle** opposes that movement.
Thus, during elbow flexion, the biceps acts as the agonist and the triceps as the antagonist; during elbow extension, the triceps becomes the agonist and the biceps acts as the antagonist.

Muscle tone

A muscle is never completely “OFF”

- It always maintains a certain level of activity, even in a relaxed state.
- This basal activity is essential for maintaining **posture and balance**.
- This condition is referred to as **muscle tone**.
- Muscle tone varies among individuals depending on factors such as the level of training and other physiological parameters, and it can change significantly in pathological conditions.

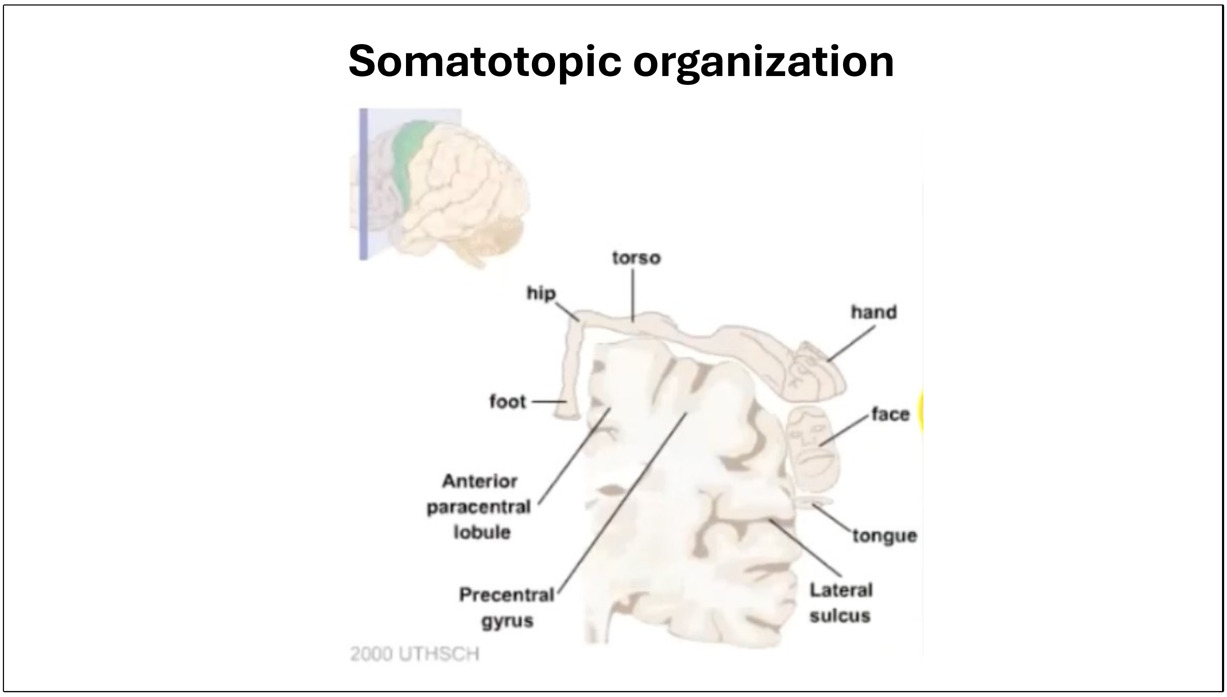


Motory cortex areas

The information that reaches the spinal cord originates from the **cerebral cortex**, specifically from a region known as the **primary motor cortex**, identified by Brodmann as **area 4**.
The primary motor cortex is the main source of motor commands directed to the spinal cord.
To better understand this, it is useful to consider the organization of the motor cortex. The motor cortex is located within the **frontal lobe** and is composed of three main areas:
primary motor cortex
premotor cortex
supplementary motor area

The functional mapping of the motor cortex was systematically described by Wilder Penfield during neurosurgical procedures performed on patients with drug-resistant epilepsy.
During these procedures, carried out under local anesthesia, Penfield applied **direct electrical stimulation of the cerebral cortex** in order to identify and preserve functionally important areas before surgical resection.
Using this approach, he observed that stimulation of specific regions of the

primary motor cortex produced involuntary movements in well-defined parts of the body. For example, stimulation of one area could evoke movements of the upper limb, whereas stimulation of another region could induce movements of the face or mouth.
These findings demonstrated that the motor cortex is organized according to a **somatotopic map**, in which different cortical regions control specific parts of the body.



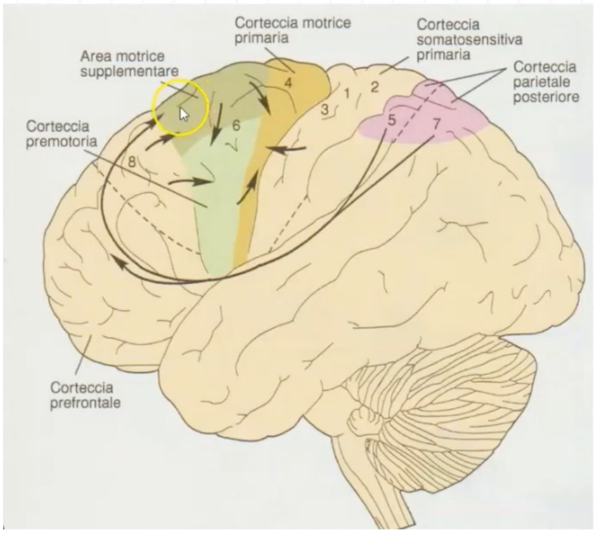
Somatotopic organization

2000 UTHSCH

This introduces a very important concept: **somatotopic organization**.
The primary motor cortex has a map, meaning that each part represents a specific part of the body.
If I stimulate the area corresponding to the face, I get a movement of the face;
if I stimulate the area corresponding to the tongue, I get a movement of the tongue.
This type of organization is also found in the premotor cortex and in the supplementary motor area.
Now let's look at the functions of these three areas.

Supplementary motor area and premotor cortex

The **supplementary motor area** and the **premotor cortex** receive information from:
some prefrontal areas, such as **area 8**
posterior parietal areas, such as **areas 5 and 7**



For a voluntary action, I first need to decide what to do.

The posterior parietal cortex and the prefrontal cortex decide the action and also anticipate its consequences.

Once the decision is made, these areas send the information to
the **supplementary motor area**
and the **premotor cortex**.

If we ask someone to simply move their fingers, we observe activation of the primary motor cortex and also the somatosensory cortex.

- *Sensory information is essential for the control of movement.*

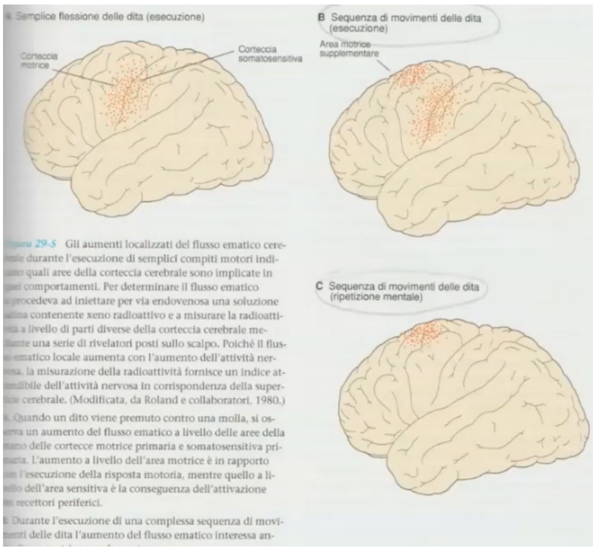
If we ask someone to perform a complex sequence of finger movements, in addition to the primary motor cortex and the somatosensory cortex, the supplementary motor area is also activated.

- *This is because the sequence needs to be planned.*

If we ask a person to only think about the sequence, without performing it, the primary motor cortex is not activated, but the *supplementary motor area is still activated.*

- *This shows that it is involved in planning.*

Just an example



29-5 Gli aumenti localizzati del flusso ematico cere-
durante l'esecuzione di semplici compiti motori indi-
quali aree della corteccia cerebrale sono implicate in
comportamenti. Per determinare il flusso ematico
procedeva ad iniettare per via endovenosa una soluzione
contenente xeno radioattivo e a misurare la radioatti-
a livello di parti diverse della corteccia cerebrale me-
te una serie di rivelatori posti sullo scalpo. Poiché il flus-
ematico locale aumenta con l'aumento dell'attività ner-
la misurazione della radioattività fornisce un indice at-
ibile dell'attività nervosa in corrispondenza della super-
cerebrale. (Modificata, da Roland e collaboratori, 1980.)

Quando un dito viene premuto contro una molla, si os-
un aumento del flusso ematico a livello delle aree della
delle cortecce motrice primaria e somatosensitiva pri-
L'aumento a livello dell'area motrice è in rapporto
l'esecuzione della risposta motoria, mentre quello a li-
dell'area sensitiva è la conseguenza dell'attivazione
recettori periferici.

Durante l'esecuzione di una complessa sequenza di movi-
delle dita l'aumento del flusso ematico interessa an-

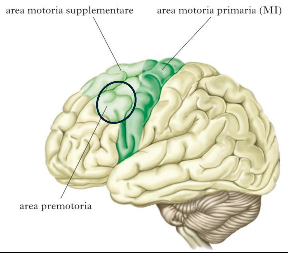
In addition, the **supplementary motor area** is important for **bilateral movements**, that is, movements requiring coordination between both hands, such as buttoning a shirt.

Mirror Neurons

In the premotor cortex, mirror neurons have been discovered.

These neurons are activated both when we perform an action and when we observe someone else performing the same action.

EXAMPLE:
Newborns, for example, respond to human faces very early thanks to the activation of mirror neurons.



Primary motor area

The primary motor cortex is responsible for the initiation of movement.

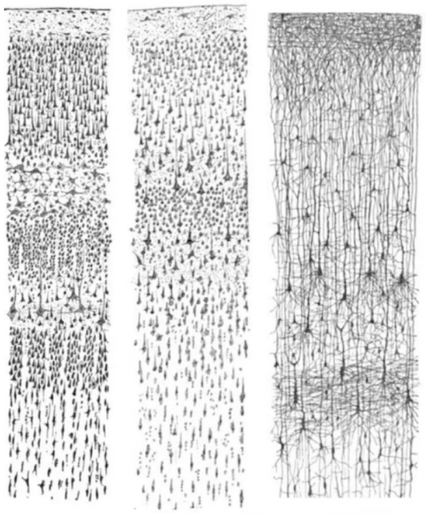
It becomes active a few milliseconds before muscle contraction, so it represents the trigger of movement.

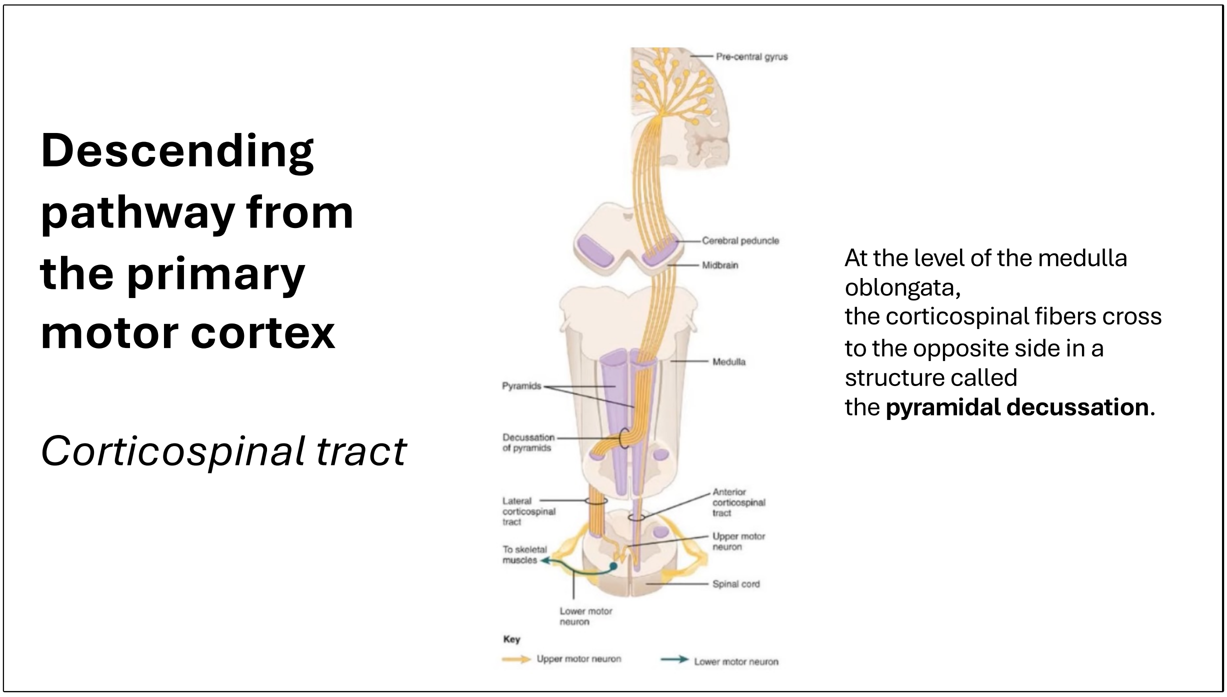
It is characterized by the presence of giant pyramidal cells, also called **Betz cells**.

These cells (**upper motor neurons**) send their axons to the spinal cord, where they activate the motor neurons in the spinal cord (**lower motor neurons**).

→ **CORTICOSPINAL CIRCUIT**

The information for movement starts from these cells, which send signals about the movement to be performed directly to the spinal cord, specifically to the anterior horns.





Descending pathway from the primary motor cortex

Corticospinal tract

At the level of the medulla oblongata,
the corticospinal fibers cross
to the opposite side in a
structure called
the **pyramidal decussation**.

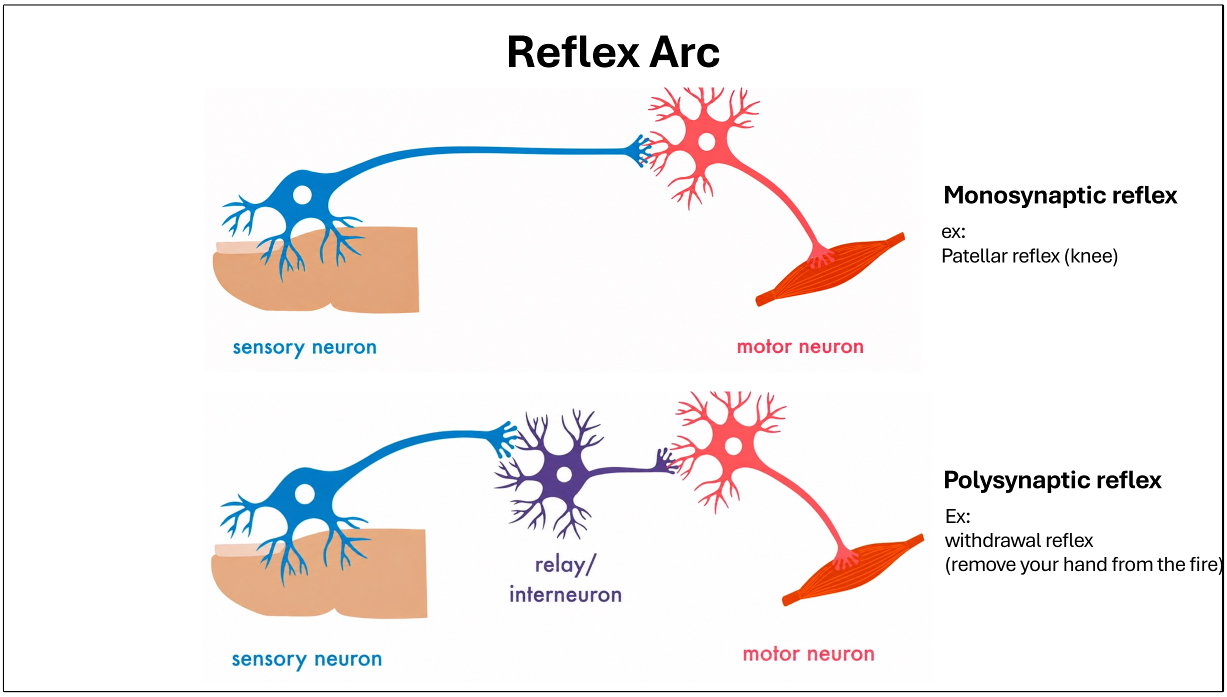
At the level of the medulla oblongata, corticospinal fibers cross to the opposite side.
Right brain → left body
Left brain → right body
This explains why a person with a stroke on the right side has paralysis on the left side, and a person with a stroke on the left side has paralysis on the right side.
If the lesion occurs below the medulla, the paralysis is on the same side.

Tu summarize

The upper motor neuron sends information to the spinal cord through the corticospinal tract.

The axons of the upper motor neuron make contact with lower motor neurons, which send signals to the muscle through the neuromuscular junction. Acetylcholine is released, and the muscle contracts.

The **upper motor neuron** uses **glutamate**, one of the main excitatory neurotransmitters in the brain.
The **lower motor neuron** uses **acetylcholine.**



Reflex Arc

Monosynaptic reflex

ex:
Patellar reflex (knee)

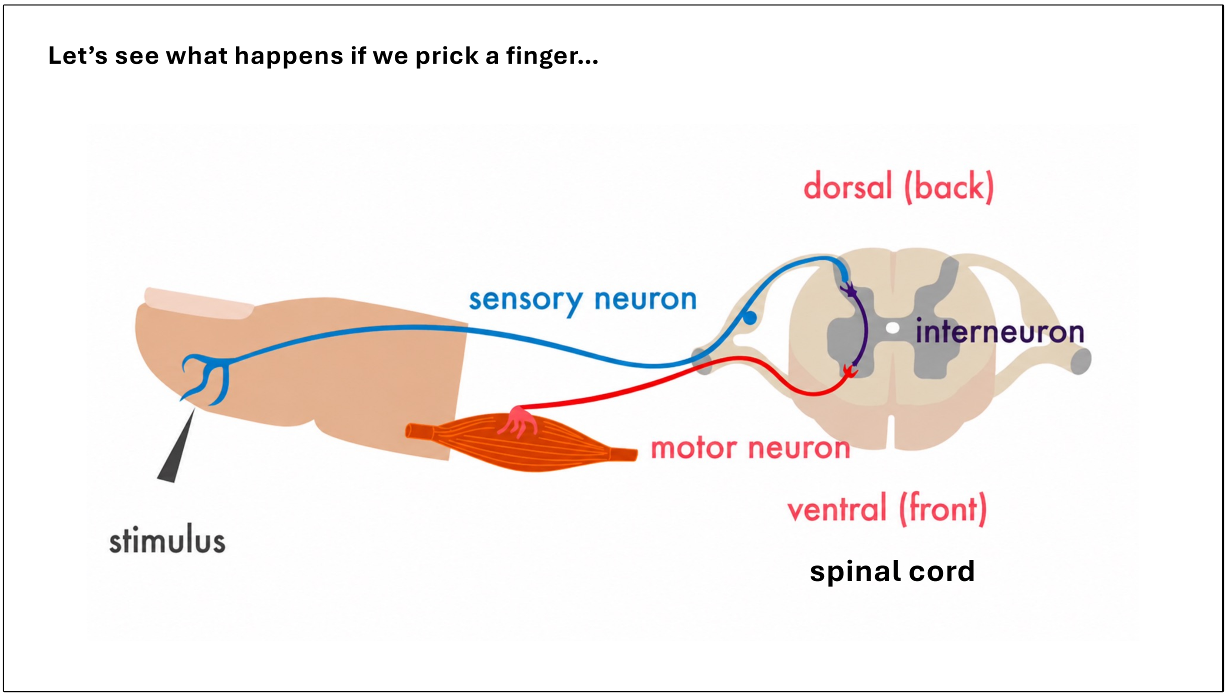
Polysynaptic reflex

Ex:
withdrawal reflex
(remove your hand from the fire)

The contraction of agonist and antagonist muscles is a voluntary process, but it is supported by many involuntary mechanisms that start at the level of the spinal cord.

One of these mechanisms is the **reflex arc**, one of the simplest neural circuits in our body.
It is an involuntary response to a stimulus.
In this response, a sensory neuron is connected to a motor neuron.
The connection can be:
direct → called a monosynaptic reflex arc
indirect → through an interneuron → called a polysynaptic reflex arc
The central nervous system includes the brain and the spinal cord.
The reflex arc takes place in the spinal cord, without the involvement of higher brain centers.
So, it does not need the brain to generate the response.

Curiosity:
The reflex arc plays an important role already in the first days after birth.
From birth, primitive (or archaic) reflexes are present and active.
These are automatic and involuntary motor patterns, controlled by the brainstem, and are essential for survival, protection, and neuromotor development in newborns.



Let’s see what happens if we prick a finger…

Let’s see what happens if we prick a finger:
The stimulus is detected by a sensory receptor and sent to the spinal cord through an afferent sensory neuron.
This neuron connects with a motor neuron, which activates the muscle and produces movement, often through an interneuron.
The response is very fast and automatic.
We become aware of it only after the movement has already happened.
In fact, the sensory neuron enters the spinal cord and splits into two signals:
one for the reflex response
one that goes up to the brain (ascending pathway)

There are many reflexes of this type:
patellar, plantar, Achilles, triceps, biceps, radial, and jaw reflex.
For example, the patellar reflex is tested by the doctor by tapping below the kneecap, which stretches the quadriceps tendon.

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