Development of Complex Curricula for Molecular Bionics and Infobionics Programs within a consortial* framework**

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**Molekuláris bionika és Infobionika Szakok tananyagának komplex fejlesztése konzorciumi keretben

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Neuromorph Movement Control

Neuromorf mozgás szabályozás

Neural structures participating in motor control

(A motoros vezérlésben résztvevő neurális struktúrák)

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Based on lectures given by Dr. József TAKÁCS C.Sc

Main points of the lecture

- **Human nervous system (central nervous system and peripheral nervous system) contains different systems in movement generation/coordination**
- **Such neural systems are summarized and presented in this lecture**
  - **Somatosensory system**
  - **Main reflexes**
  - **Basal ganglia**
  - **Cerebellum**
- **Basic organizations and functions of these neural systems are also investigated**

Somatic nervous system

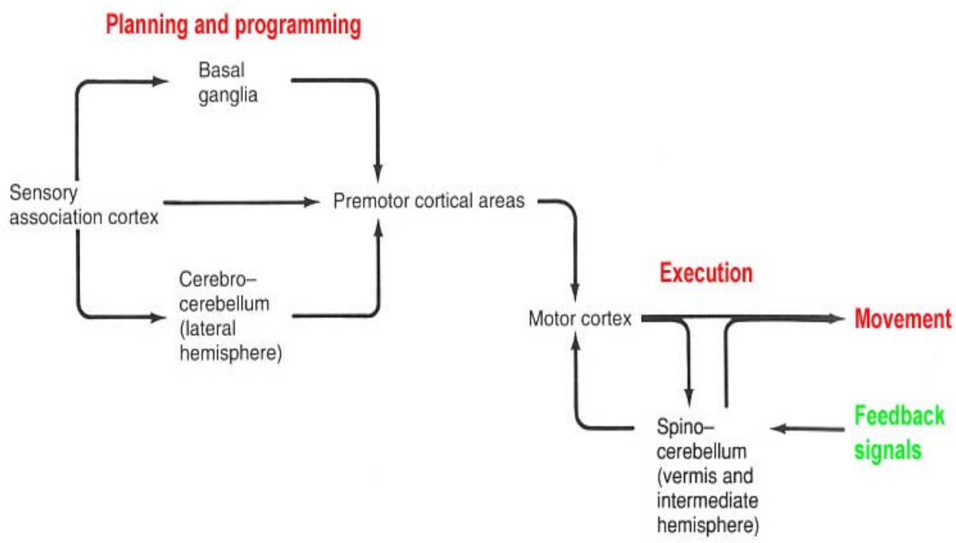
- **Somatic nervous system is responsible for the motor activity of the body**
- **Generally 2 types of activities are discerned:**
  1. **Skeletal muscle activity**
     - These voluntary functions are controlled by the somatomotor system which is constituted by the somatic nerve fibers
  2. **The activity of smooth, cardiac muscles and other tissues**
     - These involuntary functions are controlled by the visceral nervous system
- **The control of the skeletal muscles is one of the main tasks of the central nervous system (CNS)**

Somatic nervous system

- one part of the peripheral nervous system.
- Its main task is the voluntary control of body movements by using skeletal muscles

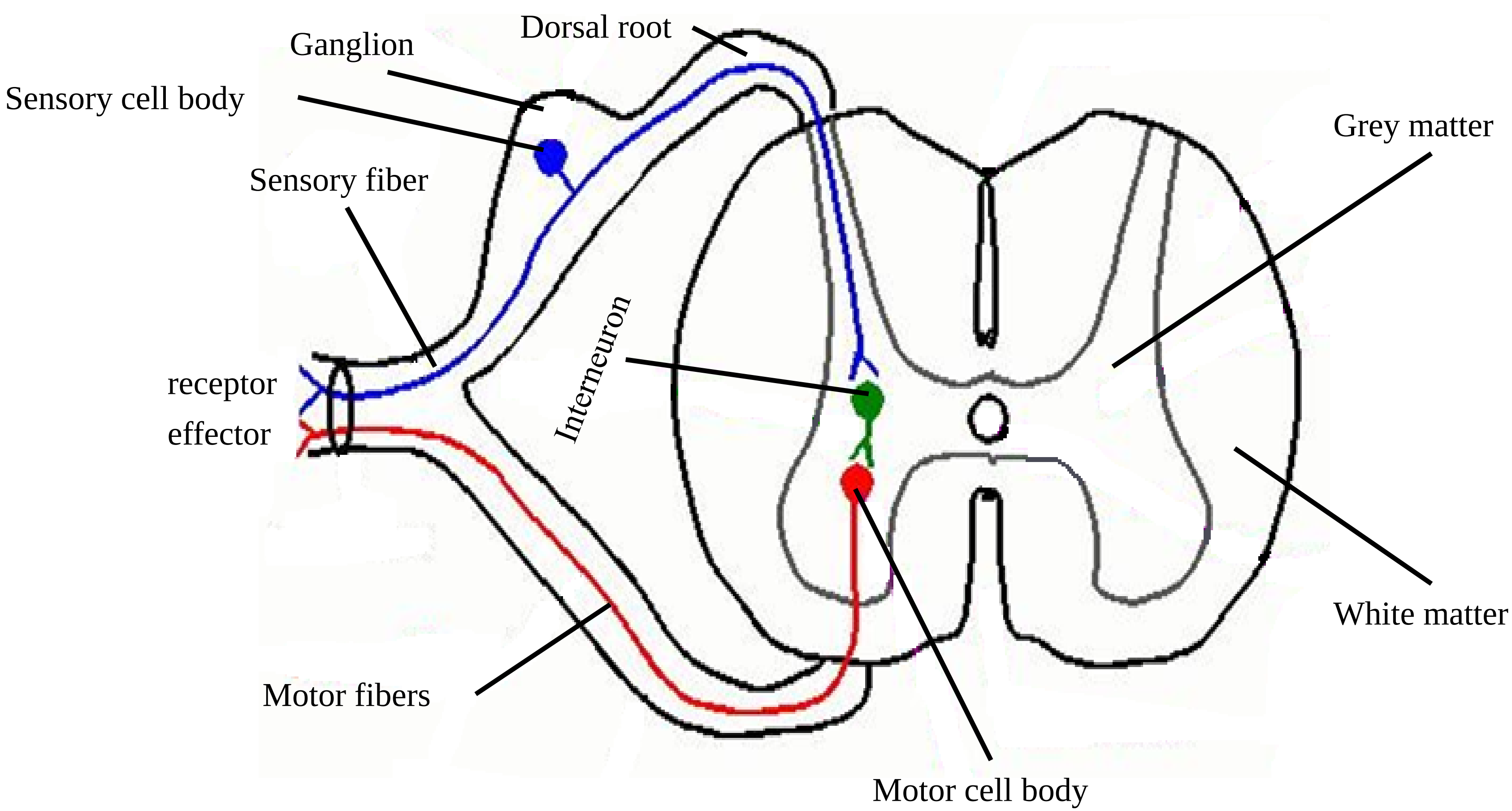
- The **Somatic nervous system** basically **consists of efferent nerves** that are responsible for **stimulating/controlling muscle contraction**, including all the neurons connected with skeletal muscles or an sensory systems
- Another main issue is the capability of sensing external stimuli
  - This is done by a complicated sensory reception system (touch, hair, eye etc…)
- **The somatic nervous system is a hierarchical system**

Somatic motor system – The hierarchy



- Block diagram of the motor system
- Earlier studies revealed a strong hierarchical organization of the somatic motor system
- The connection between the cortical centers and the spinal cord is an important part of this system.

Somatic motor system – The structure of the spinal cord



Somatic motor system

- **The continous well functioning of the motor system is based on transmitted information from the sensory systems**
- **Thus:** in the execution of voluntary movements sensory information plays a vital role

- **Information on the state of muscles intended to be activated by the CNS is generated by proprioceptors**
  - Muscle spindle
  - Golgi tendon spindle
- The information from spindles (muscle-Golgi tendon spindle) is brought by **spinal reflexes**

Somatic motor system – Muscle spindle

- **Muscle spindles:** are sensory receptors within the belly of a given muscle.
- **Primary task:** is to detect muscle length changes of the given muscle.
  - The actual state of muscle length is transmitted to the CNS via sensory neurons.
  - The information about the strain of the muscle is processed by the CNS and determines the exact position of body parts.

Somatic motor system – Muscle spindle

- **Secondary task:** to give feedback of the changes in muscle length to regulate any contraction of muscles, by activating motoneurons via the stretch reflex to resist muscle stretch.

- Muscle spindles are found within the belly of muscles, embedded in extrafusal muscle fibers
- Muscle spindles are composed intrafusal muscle fibers
  - **Types of intrafusal muscle fibers:** dynamic nuclear bag fibers; static nuclear bag fibers; nuclear chain fibers

- Furthermore: axons of gamma motoneurons end in muscle spindles
  - **Primary task:** is to ensure/generate synapses at the intrafusal muscle fibers
- Muscle spindles are encapsulated by connective tissue, and furthermore they are aligned parallel to extrafusal muscle fibers

Somatic motor system – Golgi tendon

- The **Golgi organ:** is a proprioceptive sensory receptor organ located at the juction of the insertion of skeletal muscle fibers and tendons of skeletal muscle.

Golgi tendon

- **Primary function:** is to provide sensory information of the tendon reflex.
- **When muscle force is generated:** the sensory terminals will be compressed. It will deform the terminals of the afferent axons and open stretch-sensitive ion channels.
- As a result, the axon is depolarized and generates impulses to the direction of the spinal cord.

- Tendon organs detect and respond to changes in muscle tension that are caused by passive stretch or muscular contraction

Somatic motor system

- The number of muscle spindles in humans is between: 25000-30000
  - In the arm at least 4000 muscle spindel are located while at the same time
  - In a leg 7000 muscle spindle can be found.
  - The number of Golgi tendos in all extremities are nearly 60% of the amount of muscle spindles.
- The number of both muscle spindles and Golgi tendons is different in different muscles depending on:
  - the volume and function of the given muscle

Sensory fibers - Classification

I.a.

- Goes from the chain and bag nuclear fibers (static and dynamic) of the muscle spindle to the spinal cord.
- Sensitive to muscle length and rate of change of length

I.b.

- Goes from the Golgi Tendon Organs to the spinal cord.
- Sensitive to muscle tension

II.

- Goes from the chain and bag nuclear fibers (static) of the muscle spindle to the spinal cord.
- Sensitive to muscle length

Somatic motor system – Motor function of the spinal cord

- **The underlying principle of movement generation in the spinal cord is located in the anterior horn of the spinal cord**
  - **This is called:** α-motoneuron
- **Motor Unit:** (details in lecture number 4,9**)** is a functional unit composed of a motor neuron and muscle fibers innervated by the motor neuron.
  - In case of motor neuron damage: innervated muscle fibers will lose their functions
- **Primary** task of α-motoneuron: generating reflex (response to the sginals from the peripherals)
- **Secondary** task of α-motoneuron: transmits commands from higher control levels

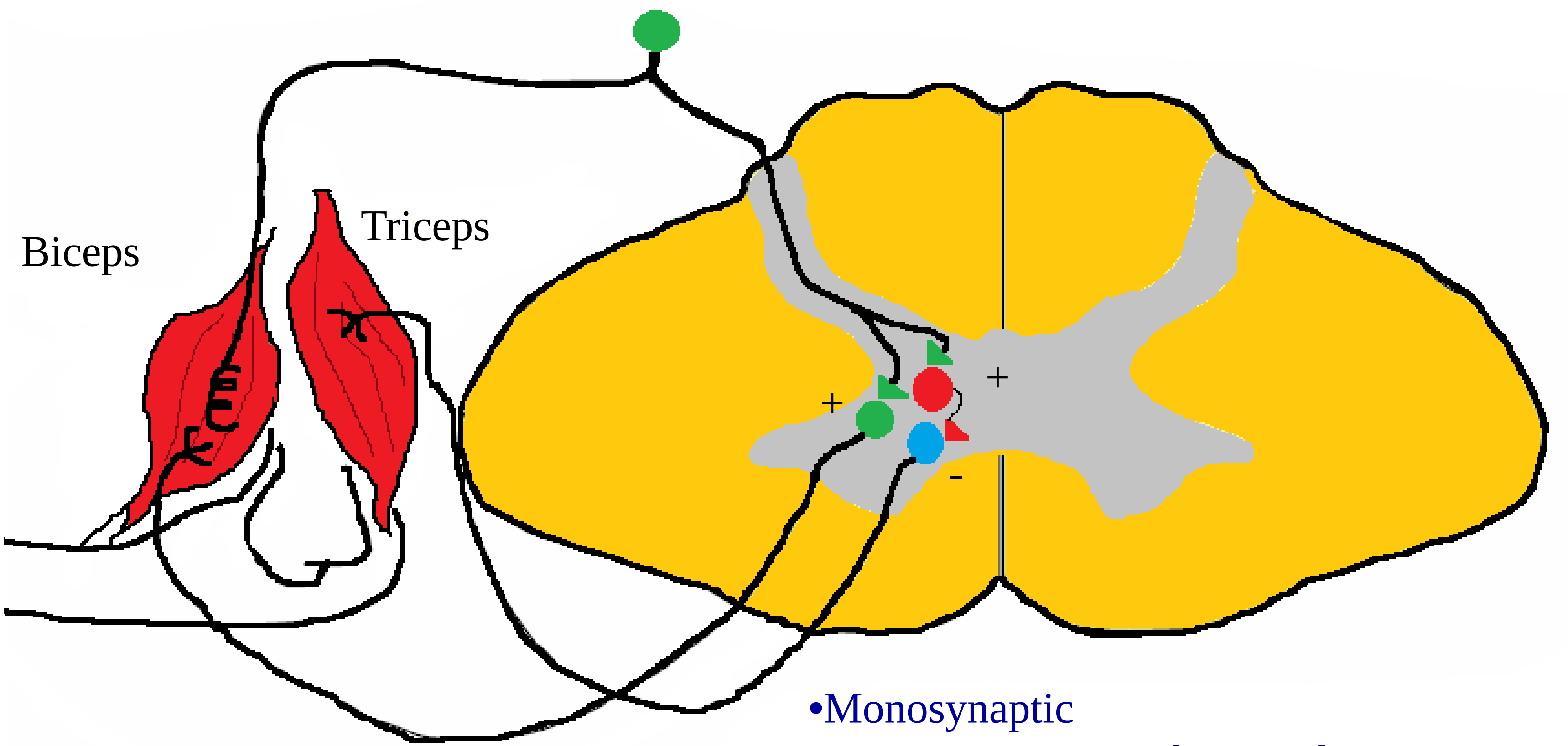
Somatic motor system – Reflex action

- **A reflex action:** is an involuntary and nearly instantaneous movement in response to a stimulus coming from the peripherals.
- **Reflexes are transported via reflex arc**
- **Classification of reflexes:**
  - **Number of synapsis**
    - Monosynaptic (reflex arc consists of only two neurons)
    - Polysynaptic (one or more interneurons connect afferent (**sensory**) and efferent (**motor**) signals)
  - **Types of receptors**
    - Proprioceptive
    - Skin reflexes

Somatic motor system – Reflex arc

- **The main question is: How the Message Travels From the Receptor to the Effector?**
- **A reflex arc:** is a neural pathway that mediates a certain reflex action
- Nerve cells (**neurons**) carry the message from the stimulated receptors to the correct effectors.
- A **sensory neuron** carries the message from the receptor to the **central nervous system** (to the spinal cord and brain).
- A **motor neuron** carries command generated from the central nervous system back to the effector.

Somatic motor system – Schematic figure of stretch reflex



- Monosynaptic
- Serves to maintain the muscle tone
- Feedback system keeping the muscles around a set length

Somatic motor system – Stretch reflex

- **When the muscle is stretched: it results in stretching of the intrafusal muscle fibers** within the muscle spindle.
  - Result: I.a. endings will be stretched and increase firing.
- They make excitatory connections:
  - on the α-motoneuron innervating the given muscle
  - on those α-motoneurons innervating synergistic muscles.
- **Thus:** muscle contracts and its length is reduced. (**shortening**)

- I.a. fibers can also synapse on inhibitory interneurons and cause the relaxation of the antagonist muscles. (**polysynaptic component**)

Somatic motor system – Flexion withdrawal reflex

It is a polysynaptic,protective reflex: the limb is quickly moved from a painful stimulus, usually by the sudden and simultaneous contraction of all flexor muscles in the given limb

When there is a painful stimulus, the sensory signal **excites** the motor neurons innervating flexor muscles and inhibits motor neuron innervating the extensor muscles of the limb **(reciprocal innervation)**

Also, the reflex can produce an opposite effect in the contralateral limb to enhance postural support.**(crossextension reflex)**

Somatic motor system – Golgi tendon reflex

- The **Golgi tendon reflex** is the part of the reflex arc of the peripheral nervous system.
  - **In which:** skeletal muscle contraction causes the muscle to lengthen and relax at the same time.
- It is called the **inverse myotatic reflex:** ***because it is the inverse of the stretch reflex.***
- Though muscle tension is increasing during the contraction, α-motorneuron in the spinal cord supplying the muscle are inhibited.
  - However, antagonistic muscles are activated.

Somatic motor system – Golgi tendon reflex

- **Its main function:** is **to protect** the muscle from extremily heavy loads
  - by making the muscle relax and hence drop the load.
- **Stretch reflex vs. Golgi tendon reflex**
  - **The stretch reflex** operates as a feedback mechanism to control muscle length (**result:** muscle contraction)
  - **The tendon reflex** operates as a feedback mechanism to control muscle tension (**result:** muscle relaxation)
    - **Before the exerted muscle force exceeds a threshold that causes the tendons to be splitted**

Somatic motor system – Muscle tone

- **Muscle tone:** is the continuous and passive partial muscle contraction.
- **It helps:**
  - the CNS to maintain a given posture
  - To maintain the balance of the body

- **By tonic reflex:** retaining the muscle in a temporary contracted state.
  - If a stretch occurs, the body responds by increasing the muscle's tension
- **In this meaning:** muscle tonus describes a steady state condition.
  - **Furthermore:** Both extensor and flexor muscle, even in resting maintain a constant tone

Representation of voluntary movements in the cortex of the brain

- **The motor representation (motor cortex) is located in the fontal lobe of the brain**
  - In front of the sulcus centralis
- The primary motor cortex is found in the Brodman 4 area
  - All the muscles of the human body are represented here near to each other
- **Motor homunculus:** finger, hand, face are repsented on a bigger area than the whol upper and lower limb.
- Cells located in the primary motor cortex are arranged in column wise

Representation of voluntary movements in the cortex of the brain

- **Further important areas involved in the controlling of different movements:**
  - Pre-motor cortex (lateral side of Brodman 6) (PMC)
  - Frontal eye field (Brodman 8) (FEF)
  - Posterior parietal cortex (Brodman 7) (PPC)
  - Supplementary motor cortex (medial side of Brodman 6) (SMC)
  - Anterior cingular cortex (on the medial side of the frontal lobe) (ACC)
- **Within these:** there are some special areas e.g. **FEF** and **PPC** that are responsible for either eye movement control or visual control of movements, respectively

Functions and possible loss of functions in case of injury of the main motor areas

- **Primary motor cortex:** generates the „1st" command to start a voluntary movement.
  - **The primary motor cortex needs a high amount of information**
  - **Example:** if the movement is a complex one the Brodman 6 areas are involved in planning the sequence of movement execution befor generating motor command
  - **Furthermore:** the information of both the basal ganglia and the cerebellum is transmitted via the thalamus
  - Affarent information arrives from the somatic motor system as well

Functions and possible loss of functions in case of injury of the main motor areas

- **PMC:** plays a vital role in planning/preparing the movement
  - **In case of injury:**
    - Complex movements can not be either executed or planned
    - Note that muscle would be capable of movement execution
- **SMC:** solves 3 important task like a central pattern generator
    - The exact movement planning
    - Preparing movement patterns
    - Controlling of speech
  - **In case of injury:**
    - Dumb patient
    - Akinesis

Basal Ganglia (BG)

- **The basal ganglia:** is important to life nuclei in the brain interconnected with the cerebral cortex, thalamus and brainstem.
- **Basal ganglia have many functions such as**: motor control, cognition, emotion, learning
- **Parts of BG:**
  - the striatum (**putamen, caudate nucleus, nucleus accumbens**)
  - Globus pallidus(**internal and external segments**)
  - subthalamic nucleus (**STN**)
  - Substantia nigra(**SN**) - compacta (**SNc**), reticulata (**SNr**)

Basal Ganglia –

Main parts (Striatum)

- The **striatum** is a subcortical part of the telencephalon.
- It is one of the most important part of the basal ganglia system: **input**
- **Function:**
  - planning and modulation of movement pathways
  - involved in a variety of other cognitive processes involving executive function
  - is activated by stimuli associated with reward, but also by aversive, novel, unexpected or intense stimuli

Basal Ganglia –
Main parts (Pallidum)

- **In case of disfunction:**
  - Parkinson's disease (**lecture 12**) results in loss of dopaminergic innervation to the striatum
  - The lesion of the striatum is involved in the Huntington's disease (**lecture 12**), choreas, (**lecture 12**) choreoathetosis and dyskinesias.

- The **globus pallidus** is a subcortical structure of the brain.
- It is a major element of the basal ganglia system.

- **Main anatomical parts of the system:**
  - **Lateral pallidum (GPe):** receives strong glutamatergic projection from the subthalamic nucleus and sends gabaergic axons to other parts of **basal ganglia.**
  - **Medial pallidum (GPi):** receives a strong glutamatergic projection from other parts of BG and sends gabaergic axons to the **thalamus**.

Basal Ganglia – Main parts (Substantia Nigra)

- The **substantia nigra**: is a heterogeneous area of the midbrain.

Substantia nigra

- **It is responsible for:** dopamine production in the brain, and therefore plays a vital role in reward.
- It consists of two main parts:
  - **pars compacta:** contains neurons which are coloured **black** by the pigment neuromelanin that increases with age
  - **pars reticulata**: dendrites from pars compacta neurons
- **The loss or disfunction of dopamine production leads serios movement disorders like:** Parkinson’s disease

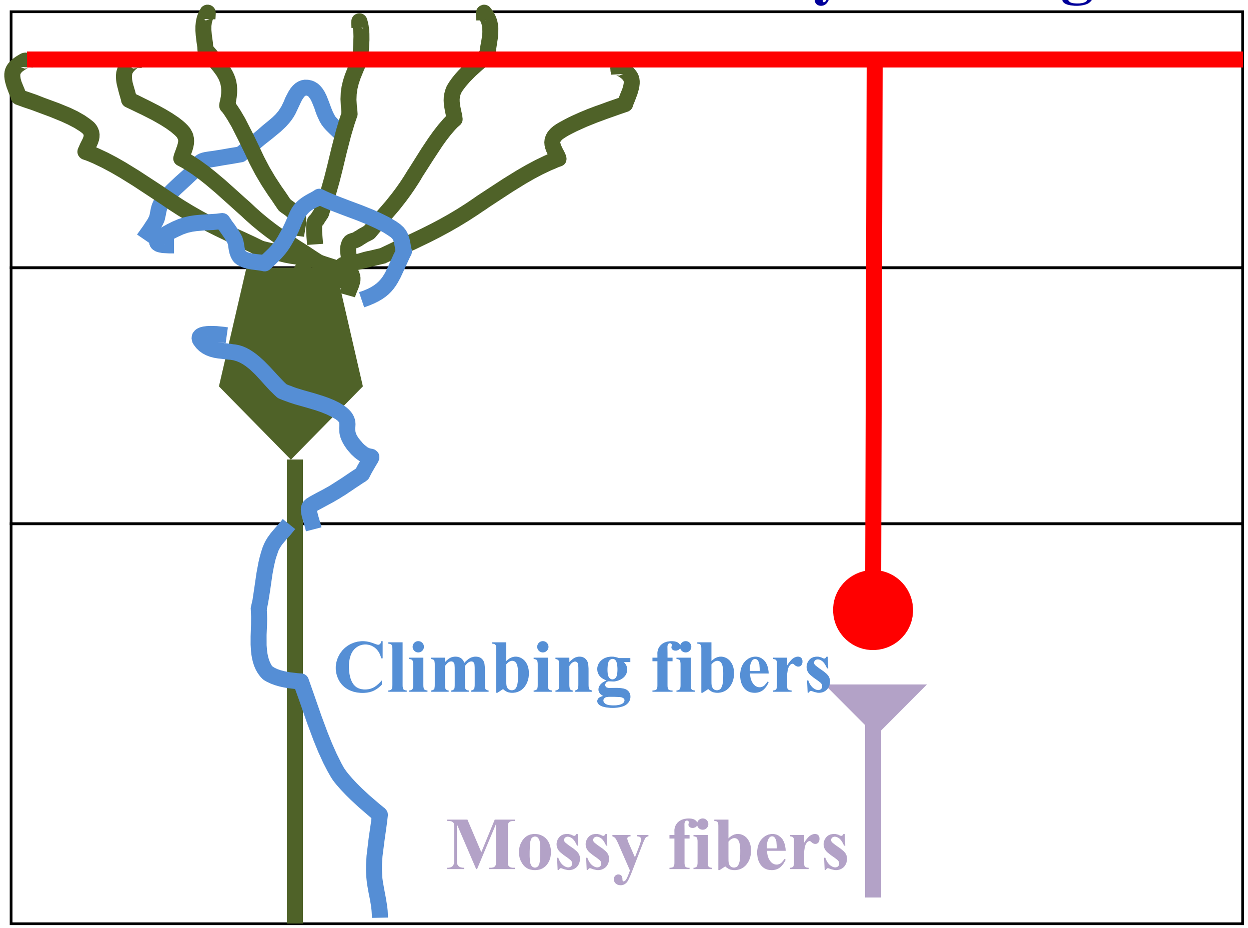
Cerebellum – Main Functions

- **Primarliy this region of the brain deals with motor coordination but it also handles some non-motor functions**
  - memory/language
- **Motor functions**
  - Coordination of movements
  - Regulation of posture
- **Acts as comparator for movements**
  - compares intended to actual performance
- **Indirect control**
  - Adjust outputs of descending tracts

Cerebellum – Main Functions

- **Motor learning**
  - Because of its layered organization it can be modeled by using neural networks
- **Correction of ongoing movements**
  - deviations from intended movement
  - internal & external feedback
- **Programs ballistic movements**
  - feed-forward control
  - direction, force, & timing
  - long term modification of circuits

Cerebellum – Layered organization



Molecular layer

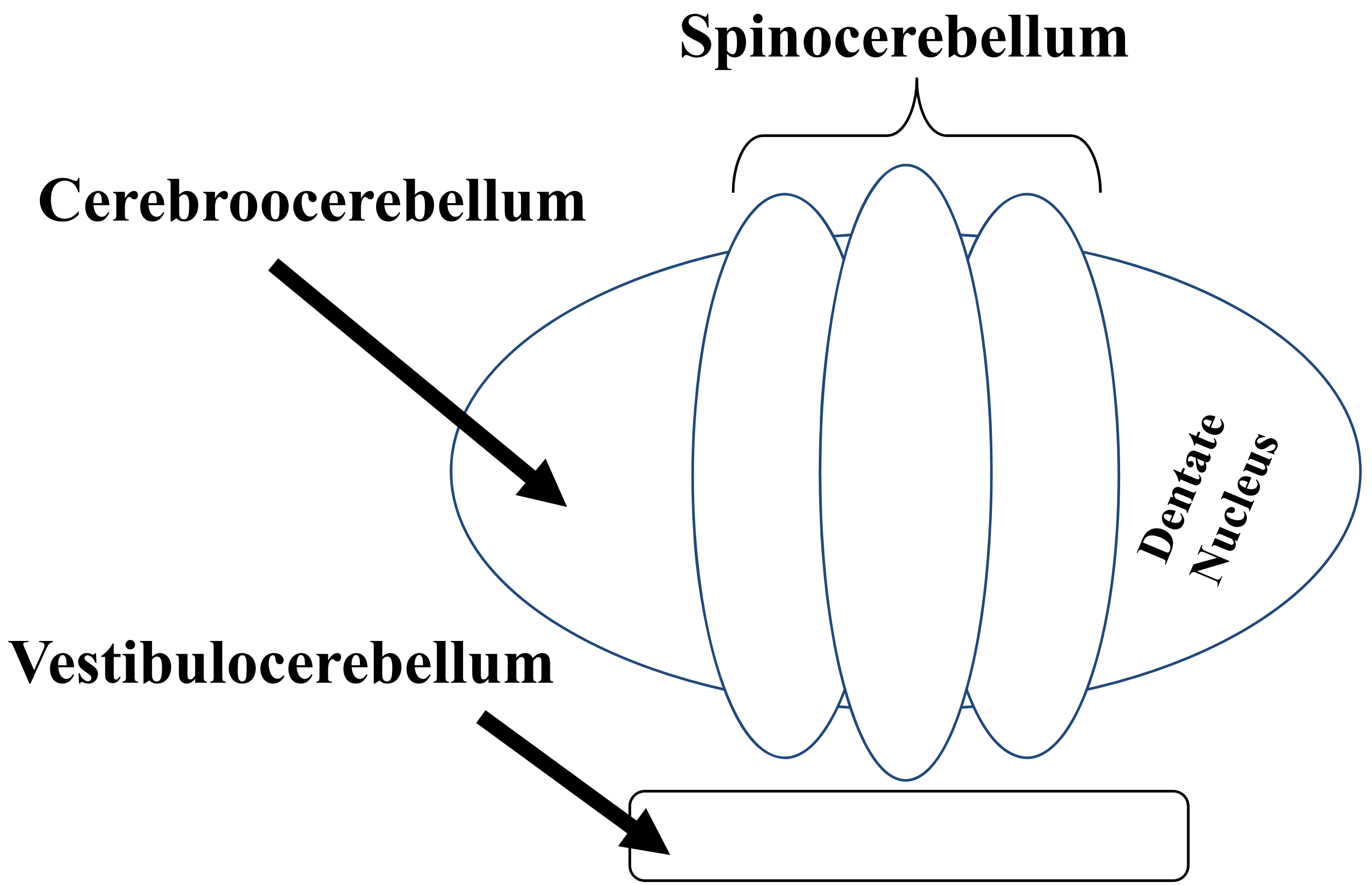
Purkinje layer

Granule layer

Cerebellum – Layered organization (Features)

- **Molecular layer**
  - parallel fibers
  - axons of granule cells
  - runs parallel to long axis of folium
- **Purkinje cell layer**
  - large somas
  - axons to white matter
- **Granular layer**
  - the innermost layer
  - small, densely packed granule cells
  - The number of neurons is greater than neurons in cerebral cortex

Cerebellum – Main Areas



Cerebellum – Functions and Lesions of the divisions

1. **Vestibulocerebellum:**
   - **In:** from vestibular organs
   - **Out:** legs, trunk, eye muscles
   - **Disorder :** loss of balance,ataxic gait
2. **Spinocerebellum:**
   - **In:** spinal cord
   - **Out:** spinal cord
   - **Disorder :** ataxic gait
3. **Cerebro cerebellum:**
   - **In:** cerebral cortex
   - **Out:** to the primary motor cortex and to PMC
   - **Disorder:** delayed and inaccurate movements

Summary

- **Main structures of the somatosensory and somatomotor system were presented.**
- **Reflexes are one of the most important actions in the peripheral nervous system**
  1. On the one hand they protect the musculoskeletal system from exceeding the limits allowed by the structures of the human body
  2. On the other hand they play a vital role in proper controling of muscle contractions and hence in movement generation
- **The main functions and anatomical structure of the basal ganglia were also presented**
- **In movement coordination and learning the role of the cerebellum is vital**

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