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NEUROPHYSIOLOGY

 CONTROL OF MOTOR ACTIVITY, POSTURE & EQUILIBRIUM

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 2

**TABLE OF CONTENTS**

Muscle structural anatomy page 3

The Cerebral cortex 9

Local cord reflexes 12

Functions of cerebellum 18

Vestibular system 23

Brainstem involvement 25

Role of basal ganglia 26

Bibliography 27

**** 3

To enable the understanding of how the nervous system brings about movement of the whole body and at the same time maintaining equilibrium, it is important to know the functional anatomy of the skeletal muscles.

Skeletal muscles are voluntary muscles and they are supplied by somatic motor nerve fibres. These types of muscle tissues when examined under the microscope show prominent transverse striations and hence are also known as striated muscle fibres. In contrast, smooth muscles which lie in our viscera and organs are non-striated and they function mostly in an involuntary manner since they are supplied by autonomic nerves

The skeletal muscles are so-called because of their close relationship to the bony skeleton and they are composed of specialized cells also known as myocytes. The main function of the myocytes is to undergo shortening or contraction, which simultaneously causes the movements of body parts.

The force generated by contraction of a muscle fibre is transmitted to other structures via connective tissues. The connective tissue which surrounds each fibre has a delicate structure and is known as endomysium, while that surrounding a fasciculus is a stronger sheath known as perimysium. The connective tissue that surrounds the entire muscle is termed the epimysium. At the junction of the muscle with a tendon, all these 3 layers become continuous with the fibres of the tendon.

Sometimes, for a movement to take place, many muscle fibres must contract at the same time in a synchronous manner and the total force of contraction would be the summation of the force generated by each muscle fibre. This summation effect is possible thanks to the presence of connective tissues around each myocyte and which connect one muscle fibre to the other. This connective tissue framework also provides pathways along which blood vessels and nerves reach each muscle fibre.

Within a muscle, fibres are arranged in the form of bundles also known as fasciculi. Both the number of fibres comprising the fasciculus and the number of fasciculi in a muscle tissue are highly variable. Small muscles like those of the vocal cords and the extra-ocular muscles have delicate fasciculi with fewer fibres in each of them as compared to larger muscles of the trunk. Muscles also differ in the way their fasciculi are arranged; e.g some are strap-like, others are fusiform, still others are bipennate and some even multipennate. The strength of contraction of a muscle depends on the number of fibres in its fasciculus and also on the number of fasciculi it contains. However, the total displacement which a muscle can produce depends rather on the length of its fibres.

**** 4

Unlike muscles, tendons are composed of parallel bundles of collagen fibres, which are united by areolar tissue containing numerous stellate-shaped fibroblasts. Their major functions are to concentrate the pull of the muscle over a relatively smaller area of bone or to allow alteration of the direction of pull on the bone by curving around bony pulleys and under retinacula and even favour displacement away from the main muscle tissue mass.

***The microscopic features of a skeletal muscle fibre:***

The diameter of a muscle fibre can vary from 10 to 60 microns in size. On cross section of a single fibre the following parts are made out:

1. **Sarcolemma**: it is the outer covering membrane, under which are located hundreds of elongated nuclei. It is itself covered on the outside by a basement membrane which enables close contact between the muscle fibre and the collagenous reticular fibres of the endomysium.
2. **Sarcoplasm**: it is the cytoplasm of the muscle fibre and it contains numerous longitudinal fibrils known as myofibrils which are uniformly distributed throughout. Besides, it also contains cell organelles as well as substantial amounts of glycogen needed for providing energy during muscle contraction. In between the myofibrils is an elaborate system of membrane lined tubules called the sarcoplasmic reticulum. Also prominent, elongated mitochondria known as sarcosomes are seen.

1. **Striae**: on examination of a haematoxylin stained preparation of a muscle fibre under a microscope using polarized light, striae of alternating dark(A) and light(I) bands are seen along the whole length of the fibre.

The A band stands for anisotropic while the I band stands for isotropic because the A bands do not refract light equally in different planes whereas the I bands do refract light equally in all directions. The phenomenon responsible for this peculiarity is most probably due to a difference in the arrangement of molecules in between both types of band, which impacts on the refraction of light when transmitted through each of them; or it may also be due to presence of a specific crystal or molecule in the different bands.

1. Other prominent **bands** noted in the myofibrils of stretched fibres are

5

 Z band, which is a thin dark line noted in the middle of each light stria (I bands).

 H zone, which is a light strip noted in the middle of each dark stria (A bands).

 M band, which is a thin dark line noted in the middle of each H zone.

The H zone was first described by Hensen and hence named after him.

These bands just described above run transversely across the entire fibre and they are really present in the myofibrils because corresponding bands on adjoining myofibrils lie exactly opposite to one another.

 The **sarcomere** is that part of a myofibril which lies between 2 consecutive

 Z bands.

***The electron microscopic features of myofibrils and sarcoplasmic reticulum:***

Under an electron microscope, a myofibril is seen to consist of 2 fine myofilaments, namely the actin and the myosin arranged in a geometrical manner. The diameter of the myosin filament is around 12 nm and that of actin is roughly 6 nm.

The A band is mainly composed of myosin filaments and the M band in it is produced by fine connections between adjacent myosin filaments. Interdigitating these myosin filaments are the actin ones, and the H zone is that region which is completely devoid of actin filaments.

The I band is made up of actin filaments alone and the Z band is a complicated network at which adjacent actin filaments of adjoining sarcomeres meet.

The actin filament is composed of 2 subfilaments or chains twisted around each other in an helical manner and is made up of actin, troponin and tropomyosin molecules.

The myosin filament is made up of a chain of myosin molecules. Each molecule has a longer tail commonly known as light meromyosin and a rounded head comprising of the heavy meromyosin. On making contact with the actin filament, the head portion bends and drags the actin filament with it; inducing shortening of the myofibrils and thence contraction of the muscle fibre. Thus, during contraction of a muscle fibre, the I band of the myofibril slides into the A band and simultaneously causes the H zone to disappear.

The sarcoplasmic reticulum is an elaborate system of tubules which lies in the intervals between the myofibrils. The larger component of the reticulum runs in a plane which is perpendicular to the axis of the myofibril and forms a ring around each myofibril. At the

**** 6

junction between the A and I bands, the myofibril is encircled by a set of 3 closely connected tubes, consisting of an upper, a middle and a lower tube which altogether constitute a muscle triad.

The upper and lower tubes are connected to those of adjacent triads via a network of smaller tubules which lie opposite each A and I bands. This network of closed tubular system is the so-called sarcoplasmic reticulum.

However, the middle tube is a separate entity which belongs to the T-system of membranes. It is called the centrotubule and is formed by the invagination of the sarcolemma into the sarcoplasm of the muscle fibre. Thus, the lumen of the centrotubule communicates with the exterior of the muscle fibre. This centrotubule plays a determinant role in the process of contraction of a muscle fibre by favouring flow of calcium ions released from sarcoplasmic reticulum into the myofibrils.

**Types of muscle fibres and their innervation:**

|  |  |  |
| --- | --- | --- |
|  Types of fibres: |  Red fibres |  White fibres |
|  Contractility  | Slow contracting fibres.Also called type 1 twitch fibres. | Fast contracting fibres.Also called type 2 twitch fibres. |
|  Sarcoplasm  | Has abundant myoglobin pigments.Nuclei may be located deeper in the fibres.Has more mitochondria and hence produce more sustained contraction.Has more glycogen and are less susceptible to fatigue. | Has fewer myoglobin pigments.Nuclei are more at the periphery.Has lesser mitochondria but more sarcoplasmic reticulum.Has lesser glycogen and are more prone to fatigue. |
|  Vascularity  | Has richer capillary bed. | Lesser vascular supply. |
|  Location  | In postural muscles which need remain contracted over longer periods. | In distal parts of limbs and muscles of vocalization which tend towards sharp active movements. |

**** 7

The white fibres are of two types, namely type 2A and type 2B. This difference arises mainly in their enzyme content and in the chemical nature of their myosin molecules.

It is also noteworthy that there are intermediate fibres which are in between the red and the white fibres.

The major arterial supply to a skeletal muscle usually enters the tissue proper at the neurovascular hilus which is closer to the origin than the insertion of the muscle. Minor vessels may enter at the ends or other places along its length. The arteries form a plexus in the epi- and peri-mysium and eventually end in capillary bed which surround each fibre. Similarly, the lymphatic system forms a plexus which extends till the perimysium but not into the endomysium.

The innervation of striated fibres also enters via the neurovascular hilus and subsequently breaks up into branches which course through the connective tissue framework of the peri- and endo-mysium to reach individual muscle fibres. The motor nerve fibres supplying skeletal muscles arise from the anterior grey horn of the spinal cord. They are the alpha efferents and the gamma efferents. The alpha efferents are large myelinated nerves which branch repeatedly to supply multiple extrafusal muscle fibres, thus forming a motor unit. The motor unit is smaller where precise control is required as in ocular muscles and larger where force of contraction is more important. Hence, the strength of a muscle contraction is proportional to the number of units activated. The junction between a nerve terminal and the muscle fibre is commonly known as a motor end plate. In contrast, the gamma efferents are smaller myelinated neurons which also arise from the anterior horn of grey matter in the spinal cord. They specifically supply special muscle fibres (intrafusal fibres) present in the sensory end receptors called the muscle spindles.

**Proprioceptive receptors:**

These receptors provide information about (i) the state of contraction of striated muscles, (ii) joint movement, (iii) joint position; all of which are necessary for precise control of movements and maintenance of body posture. These activities are regulated by the central nervous system reflex mechanisms and mostly occur at a subconscious level.

1. Golgi tendon organs- they are located at the junction of muscle and its tendon and also in the ligaments of joints. It consists of a capsule within which are concentric sheets of cytoplasm and small bundles of tendon fibres. They are innervated by branching myelinated nerve fibres and these receptors are slow adapting receptors which are activated by the pull upon the tendon either by stretch or during active muscle contraction. Impulses from them lead to reflex inhibition of adjacent muscles so as to prevent excessive stretch (which might cause tear) on ligaments.

 **** 8

1. Muscle spindles- these are sensory end organs having a fusiform connective tissue capsule and harbouring 6-14 special fibres known as intrafusal fibres. They are supplied by both motor and sensory nerves and they serve to provide the CNS about changes in length of the muscle fibre.

The central portion is midway between the ends of the fibres and has no actin or myosin filaments. Hence, they do not contract but functions as a sensory receptor.

The intrafusal fibres contain several nuclei in its mid-portion and based on their morphological arrangements, the intrafusal fibres can either be nuclear bag fibres (nuclei form a dilatation of the mid-portion) or nuclear chain fibres (nuclei are arranged in a single row).

The nuclear bag fibres are larger and they extend beyond the capsule to gain attachment to the endomysium of extrafusal fibres. They usually react to rapid changes in spindle length. They are graded as bag1 and bag2 based on their anatomical and physiological properties. Contraction of the intrafusal fibres makes the spindle more sensitive to stretch.

The nuclear chain fibres have their ends attached to the fusiform capsule and they react more slowly than nuclear bag fibres.

The motor endings on intrafusal fibres are of 3 types:

1. Gamma efferents, end at the equator of nuclear bag and do not show any typical motor end plates.
2. Gamma efferents, also called as P2 endings, end away from the equator of nuclear bag and has motor end plates.
3. Beta efferents, also called as P1 endings, are collaterals of Alpha fibres (which supply extrafusal fibres) and are located near the ends of nuclear bag fibres.

 The sensory endings are of 2 types and they both respond to stretch. The primary endings have their nerve fibres winding spirally around the nuclear region of the intrafusal fibres and thus termed as annulospiral endings. They are located on both nuclear bag as well as the nuclear chain fibres. They are rapidly adapting; while the slower secondary endings have their fibres distributed as a flowerspray away from the nuclear region and are mostly seen on the nuclear chain fibres.

Both the muscle spindle and the Golgi tendon organ are designed for ‘intrinsic muscle control’ and this mechanism operates at subconscious level. They transmit signals to the cord, cerebellum and even the cerebral cortex; so that each portion can effectively control and regulate muscle contraction.

**** 9

**The cerebral cortex.**

The cerebral cortex functions as higher centres for motor control while the lower brain areas like the brainstem, the cerebellum, the basal ganglia and the cord act as lower centres for motor function. The higher centres issue commands for most voluntary muscle movements. These impulses trigger “patterns of function” stored in the lower centres which in turn send specific control signals to the muscles.

Thus, for accurate voluntary motor function to be achievable, the interplay between various motor centres should be properly integrated. However, for fine dexterous movements of the hands and fingers, the motor cortex has an almost direct pathway to the anterior motor neurons of the cord; thus bypassing the lower centers of motor function.

The motor cortex lies anterior to the central sulcus and occupies the posterior third of the frontal lobe. It can be subdivided into 3 areas (primary motor area, premotor area & supplementary motor area); each with its own topographical representation of muscle groups as well as its specific motor functions. Posterior to the central sulcus lies the somatosensory cortex which sends sensory inputs to the motor cortex in order to initiate voluntary movements.

*Primary motor cortex*

It lies in the convolution of the frontal lobe which is just anterior to the central sulcus. Laterally, it begins in the Sylvian fissure and spreads superiorly to the uppermost portion of the cerebral hemisphere before dipping deep into the longitudinal fissure. This area is also known as Brodmann’s area 4. The topographical representation in this area was elaborated by Penfield & Rasmussen who electrically stimulated the different areas of the primary motor cortex in subjects undergoing neurosurgical interventions. The major part of the primary motor cortex is concerned with controlling muscles of hands and speech because stimulation of a single motor cortex neuron leads to excitation of a specific pattern for a group of separate muscles which on summation leads to a specific action.

*Premotor area*

It is an area which is approximately 3 cm wide and lies anterior to the primary motor cortex. It extends into the Sylvian fissure inferiorly and superiorly into the longitudinal fissure where it abuts the supplementary motor area. The topography in the premotor area is roughly the same as that in the primary motor cortex which is as follows:

* Word formation lies near the sylvian fissure (Broca’s area).
* Contralateral eye movements and
* Head rotation lie in the mid portion.

**** 10

* Hand skills lie near the apex.

Unlike the primary motor cortex, signals generated in the premotor cortex cause much more complex patterns of movement. The mechanism for these complex patterns is as follows: the most anterior part of the premotor area develops a motor image of the total muscle movement needed and this motor image is then projected to the posterior part of the premotor area, which in turn excites each successive pattern of muscle activity required to achieve that image. The posterior premotor area then sends signals to the primary motor cortex to excite specific muscles, either directly or via the basal ganglia and thalamus. This complex translation of signals is possible due to mirror neurons, which transform sensory representation of acts (either heard or seen) into motor representations.

*Supplementary motor area*

The functions of the premotor and the supplementary motor area are similar. However, the topography for control of muscle function is somewhat different here for the following reasons:

1. It lies mainly in the longitudinal fissure but extends only few centimetres into the superior part of the frontal lobe.
2. Stimulation in this area often leads to bilateral muscle contraction.
3. It works in concert with premotor area to provide body-wide (a) attitudinal movements, (b) fixation movements of different segments in the body and (c) positional movements of head and eyes.
4. It also acts as a background for finer motor control by premotor area and primary motor cortex for regions over the arms and hands.

*Other cortical areas for highly specialized motor functions*

|  |  |  |
| --- | --- | --- |
| Broca’s area | Lies immediately anterior to primary motor cortex & just above Sylvian fissure. | For word formation; but not for vocalization. |
| Closely associated area next to Broca’s area |  | For appropriate respiratory function enabling activation of vocal cords during speech. |
| Voluntary eye movement area | Just above Broca’s area | For controlling voluntary eye and eyelid movements |

 11

|  |  |  |
| --- | --- | --- |
| Head rotation area | Above voluntary eye movement area | For head rotates in the visual field. |
| Hand skills area | Lies in premotor area adjacent to its locus in primary motor cortex | For control of movements of hands & fingers. |

*The corticospinal tract (pyramidal tract).*

The pyramidal tract carries impulses from the motor cortex directly to the muscles concerned with more discrete and detailed movements. Its fibres arise from the primary motor cortex, the premotor area and the supplementary motor areas; with the greater contribution arising from the somatosensory area.

From the motor cortex, the fibres course through the posterior limb of the internal capsule (between the caudate nucleus and the putamen) till the brainstem where it forms the pyramids of the medulla oblongata. Then, it divides into the lateral and the ventral corticospinal tracts.

The lateral CST contains the majority of pyramidal fibres and these cross to the opposite side in the lower medulla before entering the cord. They end mostly on interneurons in the intermediate region of grey matter. Few end on sensory relay neurons in dorsal horn and still fewer end on anterior motor neurons.

The ventral CST contain fibres which do not cross in the medulla but run ipsilateral till the cord. most fibres then cross to the opposite side in the upper cord region (either cervical or upper thoracic). They may be associated with control of bilateral postural movements associated with supplementary motor cortex.

Within the pyramidal tract, most fibres are small diameter fibres and only 3% of its fibres are large neuron fibres. The small fibres conduct background muscle tone signals to motor areas of the cord. The larger fibres originate from large giant pyramidal cells also termed as Betz cells which are only found in the primary motor cortex.

*The extrapyramidal system.*

This terminology was used to denote all portions of the brain and brainstem which contribute to motor control but do not belong to the direct CST pathway. This includes pathways coursing through the basal ganglia, the vestibular nuclei, the reticular formation of the brainstem and often the red nucleus as well. This group of pathways is so diverse that it is difficult to ascribe specific neurological functions to its system. However, the CST

**** 12

and the EPS are extensively interconnected and they interact to control muscle movements.

The motor cortex is mainly controlled by signals from the somatosensory system and other sensory systems like hearing and vision. After receiving these sensory signals, the motor cortex works in association with cerebellum & basal ganglia in order to excite an appropriate course of motor action. The main sensory pathways are from adjacent regions of the cerebral cortices, from the corpus callosum and from the thalamus. the ventrolateral & the ventroanterior nuclei of thalamus receive signals from cerebellum and basal ganglia. These nuclei then relay signals to the motor cortex via tracts which are responsible for coordinating control of motor functions between the motor cortex, the basal ganglia and the cerebellum.

Every contraction produced in a muscle sends somatosensory signals back to the motor cortex, especially the neurons initiating the contraction. Sources of these somatosensory signals are from the muscle spindles, the Golgi tendon organs and the overlying tactile receptors. Very often these somatosensory signals cause positive feedback enhancement of muscle contraction and this mechanism follows the ‘servo-assist’ reflex stimulation. An example is as follows: if the intrafusal fibres of the muscle spindle contract more that the extrafusal ones, stretch in the spindle initiates contraction. Then, signals from the spindles return rapidly to the pyramidal cells in motor cortex in order to inform them that the extrafusal fibres have not contracted adequately. Subsequently, pyramidal cells send signal to contract the skeletal fibres further. Eventually, the contraction of the extrafusal fibres parallels that of the intrafusal fibres.

Many cord reflex mechanisms can be activated by command signals from the brain because of the few fibres from the CST and the Rubrospinal tract which impinge directly on the anterior motor neurons in the grey matter of the spinal cord.

**The spinal cord.**

Every single cord segment has neural circuitry in its gray matter. The gray matter is the integrative area for cord reflexes. Sensory signals enter the cord via the sensory root (dorsal root) of the gray matter and subsequently divides into two branches. The shorter branch is responsible for local cord reflexes and local effects while the longer one transmits signal to higher levels in the cord or to higher centres. Each spinal cord segment has several millions of neurons in its gray matter, some act as sensory relay neurons, others as anterior motor neurons and some as interneurons.

**** 13

*The anterior motor neurons.*

These neurons give fibres that leave through anterior roots of cord and directly innervate skeletal muscle fibres. The nerve fibres are of 2 types, namely alpha motor neurons and gamma motor neurons.

The alpha motor neurons have a diameter of around 14 microns and branch many times before innervating extrafusal fibres (larger skeletal muscle fibres) and hence forming the motor end plate. A single fibre excites several hundreds of extrafusal fibres and altogether they constitute a motor unit.

The gamma motor neurons are much smaller with a diameter of about 5 microns and they are also fewer in number. The supply the intrafusal fibres located in the muscle spindles. Their purpose is to maintain and control basic muscle tone.

*The interneurons.*

They are located in the gray matter of dorsal and ventral horns as well as in the intermediate regions. They are highly excitable and often exhibit spontaneous activity. They synapse with one another and also with anterior motor neurons (AMN). Their connections with AMN are responsible for most of the integrative functions of the cord. The interneuronal pool has all the different types of neuronal circuits namely the diverging, the converging, the repetitive discharge circuits and so on which are responsible for the specific reflex actions of the cord. Most incoming signals from the brain or spinal nerves are firstly transmitted to interneurons where they are appropriately processed before transmission to AMN. Only few sensory signals end directly on AMN.

Renshaw cells are inhibitory cells lying in the anterior horn in close association with motor neurons and are involved in the process called lateral inhibition. After the axon of AMN leaves its cell body, collateral branches pass to the adjacent Renshaw cells, whose function is to transmit inhibitory signals to surrounding motor neurons and thus enabling focusing or sharpening of motor signals towards specific target group of cells. Besides, it is important to note that sensory system also has this mechanism of lateral inhibition which favours unabated transmission of the primary signal in the desired direction.

Proprio-spinal fibres are fibres which arise mostly form sensory neurons and subsequently bifurcate before they either ascend or descend in the cord from one segment to another. They provide pathways for multisegmental reflexes; especially those involved in coordination of simultaneous movements of groups of muscles in the limbs.

**** 14

*The muscle stretch reflex.*

It is a *monosynaptic* pathway which favours rapid reflex contraction of the skeletal muscle fibres with the shortest delay possible following stimulation of the muscle spindle by stretch. Besides, it also causes contraction of closely allied synergistic muscle fibres. The reflex arc consists of the following:

1. The muscle spindle which acts as a proprioceptor and is excited by sudden stretching of the midportion of the intrafusal fibres either following lengthening of the whole muscle or due to contraction of the end portions of the intrafusal fibres themselves.
2. The afferent nerve fibres (e.g type 1a nerve fibre) connects the spindle to the dorsal root of the cord. Then, a branch from this nerve enters directly the anterior horn of the gray matter where it synapses with the AMN.
3. Subsequently, the efferent nerve fibres send motor fibres to the same muscle either via alpha or gamma neurons.

Muscle stretch reflex are of 2 types, namely dynamic reflex and static reflex.

The dynamic reflex occurs only when there is a sudden change in actual length of the muscle spindle (either an increase or a decrease). Once the change in length stops, the excess impulses transmitted (in case of stretching) or if lesser number of impulses transmitted (in case of shortening); will be spontaneously abolished. The signals originate from stimulation of the primary sensory ending and last for a fraction of a second. The purpose is to oppose sudden changes in muscle length.

The static reflex occurs following slow stretching of the spindle and persists as long as the muscle spindle remains stretched. Its signals originate from both the primary as well as the secondary nerve endings and may last for minutes. The purpose is to maintain the degree of contraction at a reasonably constant level except when the person’s conscious level willfully wishes otherwise.

Stimulation of nuclear bag fibres elicit a dynamic reflex while stimulation of nuclear chain fibres elicit a static reflex. Therefore, when there is some degree of gamma nerve stimulation, the spindles emit sensory impulses continuously. As such, the spindles send to spinal cord dynamic signals to indicate stretch or shortening of a muscle fibres and static signals to indicate that the muscle is unstretched.

The principle behind the functioning of the muscle stretch reflexes is that if the spindle does not contract or relax in parallel with the skeletal muscle fibres, the receptor portion of the spindle would be either sometimes overstretched or flail.

Basic differences between dynamic reflex and static reflexes are:

****15

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| Types of reflexes |  Dynamic reflexes |  Static reflexes |
| Stimulus | Sudden brisk changes in spindle length on bag fibres. | Continuous signals from slow contracting chain fibres. |
| Sensory endings stimulated | Annulospiral – type 1a fibres having primary nerve endings. | Flowerscape – type 2 fibres having primary and secondary nerve endings. |
| Reflex accentuation | Stretch of nuclear bag | Shortening of nuclear chain |
| Reflex dampening | Shortening of nuclear bag | Unstretching of nuclear chain |
| Responding motor neuron | Gamma-d neurons | Gamma-s neurons |
| Response / purpose | Oppose the force producing the sudden changes in length of bag fibres. | Maintain steady contraction. |

Functions of the spindle reflexes are:

1. Signal averaging: since motor signals from the anterior horn of the cord vary in intensity and frequency, the subsequent muscle contraction tends to follow the same jerky pattern. The spindle reflex counteracts this irregular contraction by dampening or smoothening the muscle contraction and thus prevents jerky or oscillating body movements.
2. Coactivation of alpha and gamma motor neurons: a third of AMN are gamma fibers and the remaining two thirds are of type alpha fibers. Motor signals from higher centres are transmitted to alpha fibers; but in most instances, gamma fibres are simultaneously activated. Hence, ‘coactivation’ results in both extrafusal and intrafusal fibres being stimulated at the same time. These simultaneous contractions keep the length of the receptor portion of the intrafusal fibre in a relative proportion to that of the extrafusal fibre during the whole muscular contraction and besides, they damp the spindle stretch reflex arc from preventing the shortening of extrafusal fibres.

****16

1. Collaboration with the bulboreticular area: the gamma efferent system is excited mainly by signals from the bulboreticular facilitatory region of the brainstem, which in turn receives transmitted impulses from the cerebellum, cerebral cortex & basal ganglia. The bulboreticular area is particularly concerned with the contraction of antigravity muscles and since these muscles have a high density of muscle spindles, it has been postulated that the mechanisms of the gamma efferent system are directed towards damping the movements of the different body parts during walking and running. Besides, a major role of the spindle is to stabilize body position during tense muscular activity. This is mediated via gamma efferent system which carries signals from bulboreticular formation and allied areas from the brainstem to the intrafusal fibres, thereby causing stretching of the central portion and shortening of the end portions of the spindle receptor. This accentuates output signals from the spindle. Stimulation of the spindles on either side of a joint leads to reflex excitation of both skeletal muscles and hence, resulting in tight tense muscles around that joint. This effect leads to the joint position becoming strongly stabilized and any force trying to move it from its current position is actively opposed by the stretch reflexes. Moreover, this stabilization aids in performing additional detailed voluntary movements required for intricate motor procedures.

*The Golgi tendon reflex.*

The Golgi tendon organ (GTO) is an encapsulated sensory receptor which is stimulated by stretching or contraction of the muscle tendon fibres which course through it. It detects changes in muscle tension whereas the muscle spindle detects changes in muscle length.

The GTO also produces a dynamic as well as a static response. The dynamic response is the intense reaction lasting a fraction of a second following sudden increase in tension. However, the static response is the proportional and steady firing state which occurs at a lower intensity of muscle tension.

Its function is to provide the CNS with instantaneous information about the degree of tension in each muscle segment. At the cord level, its sensory fibres of type 1b synapse on a single inhibitory interneuron, which in turn synapses eventually on the AMN. This local circuitry has thus an inhibitory influence on effector motor neuron which causes inhibition of that individual muscle only. Besides, the signals from the GTO also synapse

****17

in the dorsal horn of the cord and from there, follow long fibre pathways like the spinocerebellar tracts to the higher centres.

The GTO reflex (also termed as inverse stretch reflex) is a local cord reflex arc that is entirely inhibitory and provides a negative feedback mechanism causing instantaneous relaxation of the entire muscle, thereby protecting that specific muscle from developing excessive tension which might otherwise lead to muscle tear or tendon avulsion. Besides, the GTO might help spread muscle load among muscle fibres, by inhibiting those experiencing excessive tension and allowing further contraction in those having too little tension by virtue of the absence of reflex inhibition.

Both the muscle spindle and the GTO apprise higher centres of instantaneous changes taking place in different muscles. The higher centres concerned are the cerebellum, the reticular areas of the brainstem and to a lesser extent the motor cortex. These impulses are necessary for the feedback control of motor signals.

*Other local cord reflexes:*

Some *polysynaptic* cord reflexes are the flexor reflex, the crossed extensor reflex and the reciprocal inhibition reflex.

The *flexor reflex* is the ipsilateral contraction of flexor muscles following the stimulation of any receptor in the skin tissue; and it may sometimes be called the *body withdrawal reflex.* The flexor reflex is so well developed in the limbs region because their cord segments have integrative centres which provide for a diverse patterns of withdrawal reflexes involving various groups of muscles (flexors, abductors, adductors, extensors, rotators, etc.). The integrative centres in the cord are formed by the interneuronal pool of neurons lying between the sensory nerves of the dorsal root ganglion ant the anterior motor neurons of the ventral root. The simplest interneuronal circuit has a pathway comprising of 3 to 4 interneurons. The basic types of interneuronal circuits are:

* The diverging circuit: for spreading of impulses.
* The reciprocal inhibition circuit: for inhibiting antagonist muscles.
* The after-discharge circuit: for prolonging the effects or actions, even after cessation of the stimulus.

All complex integrative reflexes are liable to fatigue and this applies to the flexor reflex as well.

After-discharge duration depends on the intensity of the sensory stimulus. The effects of the after-discharge can be either immediate or prolonged. Immediate ones can last for 6 to 8 milliseconds and are due to repetitive firing of the interneurons themselves. However,

****18

prolonged after-discharge is due to reverberating circuits causing recurrent pathways to oscillate, and it generally only occurs following strong painful stimuli.

Besides prolonging the residual actions, after-discharge allows time for the higher centres to trigger other CNS reflex actions (or reactions) relative to the painful stimulus.

The *crossed extensor reflex* is the extension produced in the opposite limb, ½ second after applying a painful stimulus to one limb. The peculiarity of this reflex is:

* There is crossing of signals in the interneuronal pool from one side to the opposite side.
* The only group of muscle involved is the extensor of the opposite side.
* It has a longer reaction time when compared to a flexor reflex.
* Its after-discharge is also more prolonged than that of flexor reflexes; implicating presence of only reverberating circuits.

The *reciprocal inhibition reflex* is a phenomenon which follows the principle of *reciprocal innervation,* whereby excitation of a muscle is simultaneously accompanied by the relaxation of its antagonistic group of muscles. It is commonly encountered in a stretch reflex of the muscle spindle. Stimulation of sensory (type 1a fibre) neurons from a particular muscle spindle causes post-synaptic inhibition in AMN (alpha) fibres of its antagonistic group of muscles. This is mediated via a bisynaptic pathway because a collateral from each 1a fibre synapses with an inhibitory interneuron, which later connect to AMN fibres of antagonist muscles.

**The cerebellum.**

An efficient control of motor function relies on an interplay between the higher centres. The cerebellum is called the ‘silent area’ of the brain because electrical stimulation of its neurons does not lead to any conscious sensation and barely any movement also. But, the cerebellum is an important organ for smooth and coordinated body movements. The cerebellum has 3 lobes; namely the anterior, posterior and the flocculonodular nodular one which is the oldest portion of the cerebellum and works in association with the vestibular system in order to control body’s equilibrium.

Functionally, the cerebellum can be described in 3 parts:

1. The vermis: is a central narrow strip of tissue which helps controlling muscle movements in the axial part of the body, i.e, muscles of the neck, shoulders and hips.

 ****19

1. The intermediate zone: is responsible for controlling muscle contractions in distal parts of all four limbs.

Both of the above mentioned areas receive afferent neurons from (a) their respective parts of the body and (b) corresponding topographical motor areas of cerebrum, red nucleus and reticular formation.

1. The lateral zone: It joins with the cerebral cortex to plan and to coordinate sequential movements of the body within fractions of a second.

It does not follow any topographical representation but it receives afferents exclusively from (a) premotor area of frontal cortex (b) somatosensory cortex

(c) other sensory association areas of the parietal cortex.

There are around 30 million identical functional units in the cerebellar cortex. Each unit is composed of a superficial and a deeper layer.

The superficial layer is made up of 3 layers of cells; namely, the outer molecular layer, the middle Purkinje cell layer and the inner granule cell layer.

The deeper layer contains the deep cerebellar nuclei (DCN) whose function is to emit output signals to other parts of the CNS. The DCN are continuously under the influence of both excitatory signals (via climbing fibres & mossy fibres) and inhibitory ones (from the middle Purkinje cells).

The **climbing** fibres originate from the inferior olivary nuclei of the medulla and once in the cerebellum, each fibre sends branches to the DCN before they reach out to the soma and dendrites of each Purkinje cells. The peculiarity of the climbing fibres is the *complex spike* they produce. The **mossy** fibres bring input signals from various parts of the CNS into the granule cell layer of the cerebellum. The mossy fibres in due course, send collaterals to the DCN.

Eventually, small axons arise from the granule cells and reach the outer molecular layer where they bifurcate into **parallel** nerve fibres, which then synapse on dendrites of Purkinje cells. Since these mossy fibres transmit weak impulses, numerous such impulses are needed to induce one *simple spike* in the Purkinje cell.

At rest, the DCN maintains a relatively constant output signal which is in favour of excitation. During execution of motor activity, the excitatory signals from higher centres stimulate the DCN but few milliseconds later, the DCN receive feedback inhibitory signals arising from the Purkinje cells. The purpose of these inhibitory signals is to damp the excitatory ones and thus prevent overshooting.

****20

Moreover, the cerebellum has 2 more types of inhibitory cells – the basket cells and the stellate cells, both lying in the outer molecule layer and stimulated by the parallel nerve fibres from granule cells. The basket and stellate cells send axons running perpendicularly to the parallel fibres and induce lateral inhibition of adjacent Purkinje cells, thereby causing ‘sharpening of signals’ and thus prevent oscillatory effect during muscular activity.

*Correlation of motor functions of cerebellum and the DCN:*

It is well known that the DCN emit output motor signals from the cerebellum to other parts of the CNS.

Firstly, the mossy fibres of the cerebellum are responsible for the smooth progression of pre-planned (voluntary) events during sequential motor activities. This is possible because at the onset of any movement, the cerebellum helps provide rapid turn-on signals to the agonist muscles and simultaneous reciprocal turn-off signals to the antagonist group. This reciprocal effect is mostly a property of the spinal cord segments; but it may also arise from the inhibitory cells of the cerebellum (Purkinje cells, basket & stellate cells) as well. Now, to initiate a voluntary contraction, signals must arise from the motor cortex. They then travel down to the brainstem and eventually in the cord pathways of reciprocal innervation. However, parallel signals are simultaneously sent from the motor cortex via the pontine mossy fibres into the cerebellum. Then, each mossy fibre sends a branch directly to the DCN which in turn emit excitatory signals either via the thalamus to the cerebral cortex and then down the pyramidal tract or via the brainstem into the cord circuitry. Summation of both signal pathways leads to accentuation of the muscle contraction. Hence, turn-on signals are much stronger. The turn-off signals to the agonists arise from the granule cells receiving the mossy fibres and which subsequently relay to the Purkinje cells. Summation of signals then produce simple spike action potential in the Purkinje cells and inhibits the DCN, causing turn-off of signals at a precise time. The inhibitory effect arising from the cerebellum during voluntary motor activity is normally precisely timed as opposed to local cord reflexes.

Secondly, the climbing fibres of the cerebellum are liable to correcting errors of muscle contractions while they are still being executed so that there is conformity between motor signals directed by the motor cortex and other parts of the brain. This is possible because the cerebellum continuously receives sensory information from peripheries and thus about sequential changes in status (position, rate of movement, forces acting on) of every body parts. Subsequently, it compares these sensory inputs to the motor commands of the motor cortex and subconsciously transmits instantaneous corrective signals to the motor system so as to modify the level of activity of specific muscles.

****21

Thirdly, the cerebellar circuit learns from errors about motor inconsistencies which have occurred earlier. Following repetitive performances, the cerebellar circuits become progressively more precise and it results in reduction of the number of impulses emanating from the motor cortex. The probable mechanism is that in response to excitation by granule cells, the sensitivity of the Purkinje cells progressively adapts and this alteration is brought about by climbing fibres from the inferior olivary complex. Once perfection is achieved, the error signaling and adjustments by climbing fibres are no more needed.

*The neuronal circuits of the cerebellum.*

The cerebellum receives afferent nerve fibres from various parts of the CNS and these fibres enter the tissue via 3 known peduncles: the superior, middle and inferior peduncles. It subconsciously collects information about movements and relative positions of different body parts.

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|  PEDUNCLES |  INCOMING TRACTS |
|  Superior Peduncle |  ventral Spinocerebellar Tract |
|  Middle Peduncle |  Pontocerebellar Tract,  also commonly known as corticopontocerebellar  |
|  Inferior Peduncle |  dorsal Spinocerebellar tract Olivocerebellar tract Reticulocerebellar tract Vestibulocerebellar tract |

Peduncles are bundles of nerve fibres connecting one part of the brain to another. The cerebellar peduncles are 3 sets of paired bundles of the hindbrain namely the superior, middle and inferior peduncles which connect the cerebellum to the midbrain, pons and medulla oblongata respectively.

The Spinocerebellar tracts are the fastest conducting fibres in the body (around 120 m/s). They apprise the cerebellum of instantaneous changes in peripheral muscle actions. They are 2 types, namely the ventral and the dorsal ones. The 2 ventral ones receive motor signals reaching the anterior horn of cord via the rubrospinal and pyramidal tracts from the brain and also patterns of motor signals generated locally within the cord itself. Thus,

****22

they inform the cerebellum of the types of motor signals which have reached the cord and provide it with an ‘efference’ copy of the motor drive on the AMNs. The ventral spinothalamic tracts end bilaterally in the cerebellum. The 2 dorsal Spinocerebellar tracts bring information from the muscle spindles and to a lesser extent from somatic receptors (GTO, tactile receptors and joint receptors). They inform about the momentary status of contractions (force and tension), body parts (positions and rate of movement) as well as forces acting on body surface. They terminate in the vermis and intermediate zone on the ipsilateral side of cerebellum.

The Cortico-pontocerebellar pathway originates from 3 cortical areas: the motor, premotor and somatosensory area. It courses to the pontine nuclei and from there, via the pontocerebellar tracts to the contralateral side of the cerebellum (into its lateral zones).

The Olivocerebellar tract brings fibres from the inferior olivary nuclei to all parts of the cerebellum, while itself receiving inputs from the primary motor cortex, the basal ganglia, widespread areas of reticular formation and the spinal cord.

The Vestibulocerebellar tract transmits impulses from the vestibular apparatus and the vestibular nuclei of the brainstem to the flocculonodular lobe and the fastigial nucleus of the cerebellum.

The Reticulocerebellar tract takes fibres from different portions of the reticular formation of brainstem to the midline areas of the cerebellum, especially the vermis.

Some pathways relay signals from the dorsal column of cord into the dorsal nuclei of medulla before reaching the cerebellum. Other pathways sending signals to the cerebellum are the Spinoreticular and the Spino-olivary pathways.

*Efferents from the cerebellum.*

To be able to execute motor commands towards a smooth progression of successive motor activity and simultaneously maintaining equilibrium, the cerebellum emits signals from its DCN to other parts of the brain. The deep cerebellar nuclei (DCN) are the dentate, the interposed and the fastigial nuclei. The vestibular nuclei of the medulla can also be considered as part of the DCN owing to the direct connections between these nuclei and the cortex of the flocculonodular lobe. These DCN receive inputs from the cerebellar cortex and the deep sensory afferents to the cerebellum. Every signal reaching the cerebellum divides into two; one directed towards the DCN and the other towards the cortex overlying the DCN. Subsequently, a fraction of a second later, the cortex relays an inhibitory signal to the DCN. Therefore, the DCN receives an excitatory signal directly and an inhibitory signal indirectly. Efferents are nerve fibres which conduct signals away from the cerebellum. They arise from specific regions of the cerebellum as follows:

****23

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| **Region of cerebellum** | **Via DCN** | **To brain structures & extensions**  | **Purpose/ actions** |
| Vermis and midline structures | Fastigial nucleus &Uvular nucleus | Vestibular nuclei of medullaReticular formation of medulla & pons | Control of equilibriumControl of postural attitudes |
| Intermediate zone | Interposed nucleus | Nuclei of thalamus; extend to cerebral cortex.Midline structures of thalamus; extend to basal ganglia and then to reticular formation & red nucleus | Coordination of reciprocal innervation in hands and fingers |
| Lateral zone (cortex) | Dentate nucleus | Nuclei of thalamus (ventroanterior & ventrolateral);extend to cerebral cortex. | Coordinating sequential motor activity initiated by cerebral cortex. |

**The Vestibular system.**

The vestibular apparatus is the sensory organ for maintenance of equilibrium. It is located in the petrous part of the temporal, enclosed in a system of bony tubes and chambers commonly known as the bony labyrinth. Within this bony structure, lies the membranous labyrinth which is the functional part of the vestibular apparatus. This membranous structure is filled with fluid called the endolymph; while the perilymph lies between the bony and the membranous labyrinths. The bony labyrinth can be divided into 3 parts, i.e, anteriorly lies the cochlea, the vestibule in the central part and the 3 semicircular canals in its posterior portion. The cochlea harbours the sense organ for hearing, while the vestibule consists of the saccule, the utricle and the endolymphatic sac. The saccule communicates with the cochlea and the saccule with the 3 semicircular canals (SCC). The SCC are 3 in number and lie in 3 different planes as follows: the anterior SCC projects forwards and bends at 45 degrees, the posterior SCC projects backwards and is also bent at 45 degrees while the lateral SCC lies in a horizontal plane. At one end of each SCC, there is an enlargement also known as the ampulla. Each ampulla shows a small crest (crista ampullaris), on top of which lies a loose gelatinous tissue with high viscosity also known as the cupula. During head rotation, the endolymphatic fluid which has a lower viscosity moves into the ampulla and bends the cupula to one side.

****24

As the cupula moves, it causes the hair tufts from the hair cells of the crista ampullaris to bend along with it, in the same direction. Each hair tuft consists of a series of mobile stereocilia arranged in ascending order with the longest non-motile stereocilium (kinocilium) being located to one specific side and all are interconnected by filamentous attachments, such that movement in a particular direction causes depolarization of the hair cells and movement in opposite direction leads to hyperpolarization. Ultimately, these signals travel via the vestibular nerve to apprise the CNS of (i) a change in rotation of the head & (ii) the rate of change in each of these 3 planes.

At rest, the hair cells emit a tonic discharge of around 100 impulses/second. During angular acceleration of the head, the endolymph and the cupula moves in opposite direction and this leads to excessive discharge of the hair cells. While the head is moving at constant speed, the cupula goes for elastic recoil and the endolymph movement gradually diminishes; thus causing the discharge from the hair cells to decrease till near baseline level. When rotation is suddenly stopped, the endolymph returns to its original position while the cupula moves in the opposite direction and hence causing the hair cells to hyperpolarize. After a lag phase, the cupula resumes its original position and this brings the hair cells back to their tonic discharge level. In any given movement, the cristae of some SCC are stimulated while others are inhibited and this pattern of stimulation gives rise to the perception of its exact direction.

The vestibular part of the membranous labyrinth has the organs known as the saccule and the utricle. The sensory organ in each is called the maculae. While the macula of the saccule lies in a vertical position, that of the utricle lies on its inferior surface and in the horizontal plane. Thus, the macula of saccule determines orientation when head is lying down while that of utricle is concerned with orientation when head is in upright position. The macula is a flat area of specialized epithelium which is covered by a gelatinous substance containing small crystals of calcium carbonate (otoliths or statoconia). Being denser than the surrounding fluid, movement of the statoconia bends the cilia in the direction of gravitational pull. In the macula, each hair cell is oriented in a different direction so that on stimulation, a pattern of depolarization takes place and this informs the CNS of the head’s orientation in space. Thus, the vestibular system is highly efficient in maintaining body’s equilibrium when the head is in a near vertical position.

The SCC senses disequilibrium only at the beginning and at end of head rotational movements and thence predicts that an equilibrium is about to be lost; whilst the vestibular apparatus aims to maintain static equilibrium (a function of the uvula in the cerebellum) as well as equilibrium during steady movements. However, it does not detect disequilibrium in an anticipatory manner. Loss of flocculonodular lobes abolishes detection of SCC signals (meant for dynamic equilibrium) but has less effect on those coming from the macula. Thus, the cerebellum acts as a predictive organ for most rapid movements of the body and for control of equilibrium.

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The primary cortical centre for equilibrium is located in the parietal lobe, deep in the Sylvian fissure and opposite to the auditory area of the superior temporal gyrus. Signals passing through the medial longitudinal fasciculus or through the reticular tracts reach the cortical centre and apprise the mind of the equilibrium status of the body.

**Brainstem involvement.**

The brainstem consists of the midbrain region as well as the pons and medulla oblongata. Grossly, the brainstem can be viewed as being an extension of the cord into the cranial cavity because it contains nuclei (both sensory and motor) for the head and face regions, just as the cord which performs same functions for the neck region and downwards. Furthermore, the brainstem acts as a relay station for ‘command signals’ from higher centres to the cord nuclei. Regarding motor function, it is responsible for subconscious and stereotyped movements and it also aims at controlling whole body movement as well as equilibrium. This is achievable thanks to the reticular and vestibular nuclei.

The Reticular nuclei are of 2 groups; namely the pontine one and the medullary one. While the pontine reticular nuclei lie in a posterior and lateral aspect of the pons and extend into the midbrain, the medullary reticular nuclei occupy the entire medulla and lie mostly ventrally and medially. These two groups act antagonistically to one another in their innervation of the antigravity muscles. The net effect of this antagonistic action is to ensure that under normal conditions, the antigravity muscles are not abnormally tense.

From the pontine reticular nuclei, fibres travel via pontine reticulospinal tract into the white matter of anterior column of cord towards the AMN which innervate axial muscles of the body (muscles of vertebral column & extensors of limb) and thus support the body against gravity. These fibres have a high degree of natural excitability since they receive strong excitatory signals from the vestibular nuclei and the DCN. Thus, when unopposed, these pontine nuclei maintain the body against gravity even without any signals from higher centres.

The medullary reticular fibres arise from the respective nuclei and travel in the white matter of lateral column of the cord to terminate on AMN supplying the same antigravity muscles. However, these fibres are inhibitory in nature since they receive strong inputs from collaterals of the corticospinal tract, the rubrospinal tract and other motor pathways. When the brain wishes to cause a standing posture, the medullary reticular system is inhibited, leading to loss of inhibition on the antigravity muscles. Failure of inhibition from higher centres occurs in decerebrate conditions and this results in overactivity of the pontine reticular fibres and hence the ensuing rigidity.

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Both reticular nuclei constitute a controllable system which is manipulated mainly by motor signals from the cerebral cortex but also from other higher centres. They provide background muscle contractions for antigravity muscles and also inhibit appropriate group of muscles so that other functions can be performed.

The Vestibular nuclei of medulla function in association with the pontine reticular nuclei in order to control the antigravity muscles. They send signals via both the medial & lateral vestibulospinal tracts which lie in the white matter of the anterior column of the cord. They receive signals from the vestibular apparatus (vestibular nerve fibres) and in response, they selectively control excitatory signals to antigravity muscles in order to maintain equilibrium.

**Role of the basal ganglia.**

Both the basal ganglia and the cerebellum are known as the accessory motor system because they function in association with the cerebral cortex and the corticospinal motor system. While the cerebral cortex initiates stimulus for muscle contraction, the other 2 organs coordinate motor function for a smooth progression from one sequence to another. The basal ganglia (i) plans complex movements (ii) controls pattern of complex movements (iii) controls intensity of specific separate movements (iv) control sequencing of multiple successive movements to achieve specific goals in complicated settings. The basal ganglia receives all input signals from the cerebral cortex and sends almost all output signals to the cerebral cortex.

The basal ganglia occupies a large portion of the interior regions of both the cerebral hemispheres and is located lateral to and surrounding the thalamus. It consists of the following masses; namely the putamen & globus pallidus, the caudate nucleus, the substantia nigra and the subthalamic nucleus. The space between the caudate nucleus and the putamen is known as the internal capsule, which contains almost all motor and sensory nerve fibres connecting the cerebral cortex to the spinal cord. thus, there is tremendous association between the basal ganglia and the corticospinal system regarding motor control. The two major circuits are the (i) putamen circuit and the (ii) the caudate circuit.

The putamen circuit is mostly responsible for executing learned patterns of movements. It has its inputs mainly from parts of the brain adjacent to the primary motor cortex which include premotor areas, supplementary areas of motor cortex, somatosensory areas of sensory cortex but not much from the primary motor cortex itself. The output from the putamen goes to the internal portion of the globus pallidus and then via relay neurons to the ventrolateral and ventroanterior nuclei of the thalamus. Then, extensions send signals back to the primary motor cortex, the closely associated premotor and supplementary

****27

areas of motor cortex.

The caudate circuit plays a major role in the cognitive control of motor activity. This occurs as a consequence of thoughts generated in the mind. It takes place at a subconscious level and determines within seconds which patterns of movement should fuse in order to achieve a complex goal. The caudate nucleus extends into all lobes of cerebrum and receives large amounts of inputs from association areas of cerebral cortex overlying it, especially from those areas which receive and integrate different types of sensory and motor information into usable thought patterns. The signals from the cerebral cortex reach the caudate nucleus and then go to the internal portion of the globus pallidus before being relayed to the ventroanterior and ventrolateral nuclei of the thalamus. From there, impulses are sent to the prefrontal, premotor and supplementary motor areas which altogether are motor regions concerned with putting together sequential patterns of movements lasting for 5 seconds or more. Eventually, they reach the cerebral cortex. The posterior parietal cortex is the locus of the spatial coordinates for motor control of all parts of the body and the relation of each part to the surroundings. The caudate circuit functions in concert with association areas of the cerebral cortex like the posterior parietal cortex and may thus be responsible for timing & scaling the intensity of motor functions via its cognitive motor control circuit.

In the basal ganglia, there are both excitatory and inhibitory systems and the interplay between them is balanced by negative feedback loops which tend to stabilize the excitatory pathways. Excitatory pathways involve cholinergic, glutaminergic and adrenergic (norepinephrine) neurons; while inhibitory pathways involve dopaminergic, serotonergic and GABA-ergic systems.

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