Neural Science for Engineers
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Lecture - 28
Polysynaptic Reflexes

Hi back again. So, in our previous session we discussed about the monosynaptic reflex. How the monosynaptic reflex works at various stages. I have started with a very simple reflex with one single synapse and 2, 3 cells and then worked my way up to the gamma motor neuron.

And how the spindle cell muscle fibers get activated and connected up the whole thing. And then I have introduced the idea of the corticospinal tract. The corticospinal tract we had seen in anatomy session on the spinal cord, and the location of the corticospinal tract.

We had also seen that the corticospinal tract goes to the opposite side of the level of the medulla in the pyramids which we have discussed in our anatomy. So, the motor cortex I had referred to the motor homunculus, where the body is represented upside down on the motor cortex.

And that is the output of the entire of the entire thought process, meaning the frontal part of the brain, anterior to the central sulcus gives an output through the motor cortex. And the motor cortex signals come down all the way through the corticospinal tracts, cross at the medulla, come to the opposite side and then come to the alpha motor neuron and to the gamma motor neuron.

So, I also said that the idea of the corticospinal control on the segment is in the negative. So, it actually suppresses the gamma motor neuron, reducing the tone of the muscle to nominal levels. And the alpha motor neuron is responsible for contraction and change within this is what is reflected in the muscle activity and muscle contraction. So, control of muscle contraction at a very basic level happens through this.

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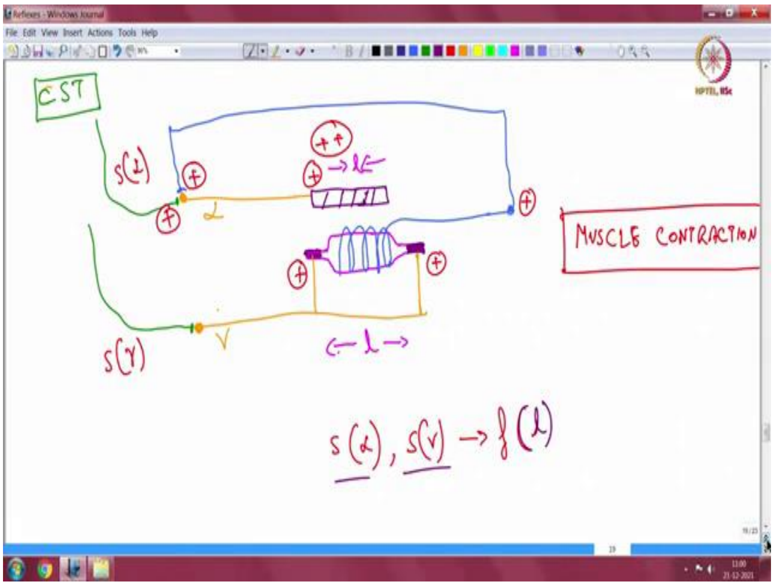

Now, that is what we have looked at in this set of diagrams. Now, we need to look at two more reflexes in the same junction.

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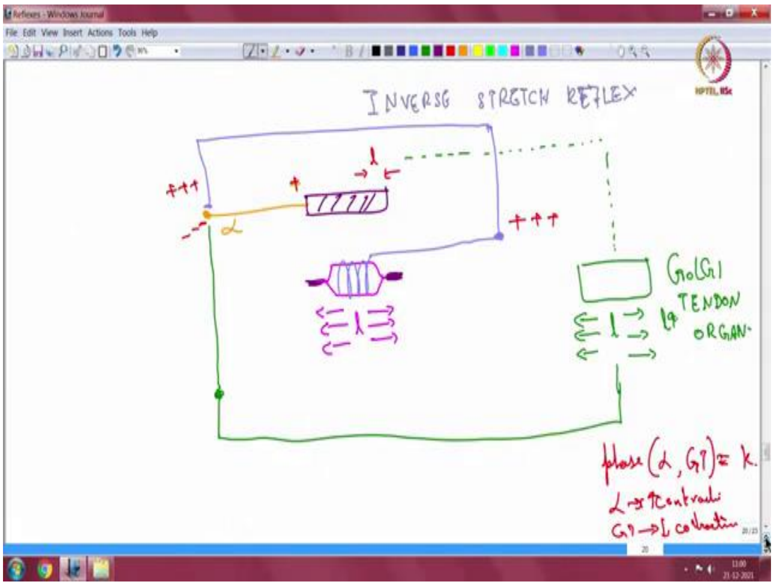

One is the inverse stretch reflex, so we draw back or system. So, alpha goes to muscle cell, then you have the spindle, and you have motor fibers in the spindle motor fibers. Then you have the complete monosynaptic stretch reflex. We will start again with this.

So, we start with the idea that we can actually extend the spindle length for a much longer duration of time, and you increase it significantly. What happens with that? So, when we actually increase the length significantly; obviously, the signal which is going to be reached over here is plus plus plus. Why? Because this spindle is getting stretched, the signal which is generated by the spindle into the neuron is plus plus plus, that in turn would cause increase activation of this alpha motor neuron.

So, this is the alpha motor neuron and that in turn causes plus plus plus and that would cause pathological reduction in length of the muscle, pathological in the sense disease. So, how do you counter that? Is there any mechanism to do that? So, both these muscle fibers are connected to something called as the Golgi tendon organ.

So, when there is a when there is a reduction in length here. So, this thing this reduction in length causes increased length here and not just any increase in length it causes a sever increase in length here. So, length is increased of the Golgi tendon organ when there is a contraction over there and that through multiple neurons causes an inhibition.

So, when that happens you have a reduction in the output of the alpha motor neuron, that in turn causes reduction in the length and it prevents pathological damage. So, these are cases or instances of activity, but in any given kind of contraction scenario, you should imagine that all of these are working simultaneously, may be out of phase.

So, I am not aware of studies which tell me phase relationship between motor neuron, spindle cell muscles, spindle and the Golgi tendon organ. So, you know simply put if the Golgi tendon organ were to work in the same phase as the alpha motor neuron.

Alpha, Golgi tendon is equal to a particular constant then there will be no muscle activity. Because as alpha causes muscle contraction, Golgi tendon prevents muscle contraction right, so Golgi works in reverse.

So, the tone which is generated by the gamma motor neuron is opposed by the Golgi tendon organ. So, there is a dynamic equilibrium. So, the dynamic equilibrium spans these three entities locally. So, these are very local. So, if we draw just the muscle circuit it would be something like this.

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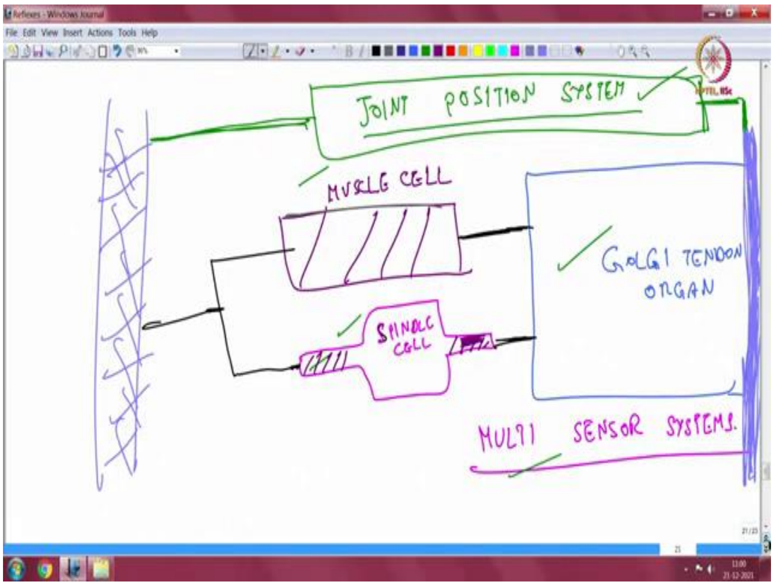

This is the schematic diagram which basically highlights what I have been discussing so far so spindle cell, muscle cell, Golgi tendon organ and all of them are together associated with this dynamics and all of them are present within the skeletal muscle. So, another highlight of this thing is the concept of multi sensor systems.

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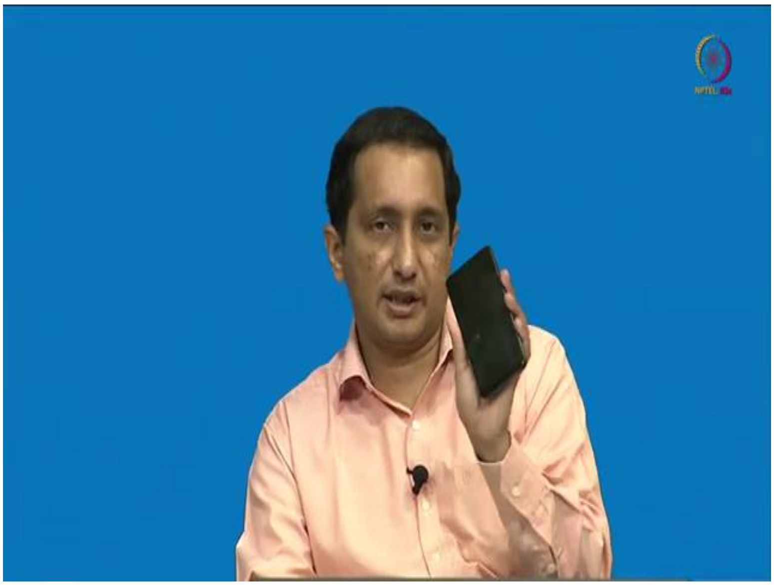

So, multi sensor system, see if you look at you know the mobile phone and you are looking at you know you want to get this direction data in a mobile phone. So, there is just one single sensor or a couple of sensors which say that this is the position of the phone and then you process that data.

If you look at single set of muscle cells, we see that it is a complex. So, there is a complex of sensor systems and actuator systems, and they are very intricately and not only intricately connected. They are very well designed such that you know the whole thing works as a network.

The idea of network function is something which is very important in biology. So, when we discuss anything IT or computational, robotics looks at the actuator side of the story and control mechanisms, the software side of the story or a chip side of the story looks only the processing part of it.

So, there is a strict, rigid compartmentalization in the engineering sciences where we analyze only; of course, that may be due to the point of problem of evolution of each of the sciences. It is not that I am saying that it is a fault, but that is how the study happens in engineering subjects to my understanding.

There is rigid compartmentalization between processing, actuation and you link processing and actuation and that is how you know you have products. But if you look at the biological side of the story you have everything happening simultaneously. So, you have a trigger system, the actuator, the sensor system and back again. So, there is a closed loop, and the closed loop is multi system. I am still not highlighting other kinds of sensor systems which are in play.

So, this is something which is present within the muscle cell. So, at the same junction I will highlight this other sensor systems which is the joint position system. So, basically both the Golgi tendon organ and the muscle cells are fixed bones.

So, obviously, for the muscle to act it has to be between two mobile bones. So, if you have a fixed bone and muscle attached to it there is no purpose of the muscle being served. So, you are looking at two sets of bones which are acted upon by this system.

So, the joint position sense, it informs the position of the joints. So, position of the bones relative to each other and if you remember a joint position system is something which goes in the posterior part of the spinal cord, midline, the fasciola senators and gracilis and that is a fast transmission.

So, output of the entire action. So, what is action? Action is decision made in the corticospinal tract which is in turn coming from the motor cortex. There is a split over there. So, one part goes to the alpha motor neuron to say how much of the muscle cell has to contract. There is also information going to the gamma motor neuron as to how much gamma motor neuron activity has to be decreased or increased.

And both in turn produces a muscle action. The muscle action is limited locally by the spindle cell activity which is in turn dependent on alpha motor neuron and the muscle cell activity also on gamma motor neuron. So, there is an output synchronization at the level of muscle cell.

Not only that; that in turn is serially connected to the Golgi tendon organ which in turn provides multi synaptic feedback back to this spinal level. Together with that you have proprioception which is outside of the muscle complex, and which tells the relative angle between the two bones and that goes all the way back up to the cortex.

So, we have started with one single muscle cell. We progressed onto the sensor system associated with that one single in the muscles sensor system. Serial associated Golgi tendon organ which is another sensor system and then the over spanning proprioceptive signal which is which encompasses all of this stuff.

So, I think this is to give you an idea of the richness of the system. And these are local you know these are at the lowest level of neuronal hierarchy and this is the richness of the network at this level.

We will step up in the next set of discussions. So, I have highlighted Golgi tendon organ, I highlighted the joint position system, the muscle cell, spindle cell, gamma alpha, multi sensor systems and the works and we are still looking at one set of muscle cells.

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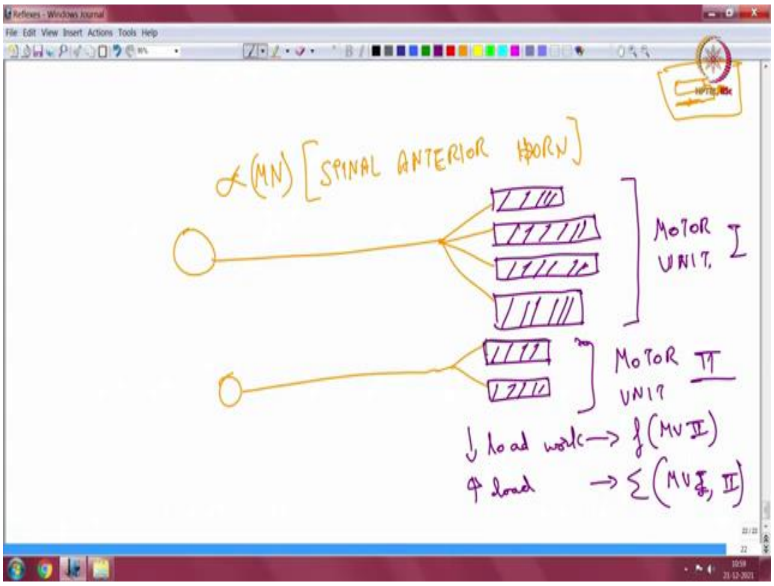

Now, concept which I think I should introduce in the same place is one alpha motor neuron which is in the spinal anterior horn innovates a set of muscle fibers. So, given signal is distributed equally in one set of muscle fibers and that is forms a motor unit.

So, the reason I am discussing is because there is a control phenomenon. Now, muscle cells as you may imagine are not very identical to each other. One there may be changes because of location, the obvious difference which I can tell you is the difference between your hands. Right hand for right-handed individuals is much stronger than left handed individuals.

And so, where is the difference? The difference is obviously, in the muscle cells. So, it is not in the neurons, it is in the muscle cells. Because the muscle cell bulk in turn determines the amount of tension which they can generate, and the amount of length change and the velocity of length change all those things are coded within the muscle cell.

So, you have one single neuron which is providing this. And please remember when I am telling muscle cell it is this entire complex. So, you have spindle muscle and Golgi tendon organ all put together.

So, this whole thing is called as a muscle cell in this current discussion. So, there are multiple such motor units of varying sizes and it is a bit of an exaggeration over here. But it is to tell you the concept that you know how tasks are relegated, as you can see here the amount of motor unit 1 and then there is motor unit 2.

So, motor unit 2 is smaller when compared to motor unit 1. So, if the brain perceives that the there is a low load work it would activate motor unit 2. And as the load increases, it would summate both motor unit 1 and motor unit 2. So, you have the option of grading power. So, power which is generated can be graded neurologically.

So, how does that happen is through the recruitment of various motor units. So, these are hardwired see please do remember that these things are all hardwired at birth literally and during development, not even during birth it may be much earlier.

So, they are all hardwired and this is a mechanism by which you can step up work based on load, based on perception, based on various kinds of input phenomena which is taken up by the nervous system. So, that is the idea of the motor unit and the purpose of the motor unit. So, from then we have spoken about I think somewhere down before.

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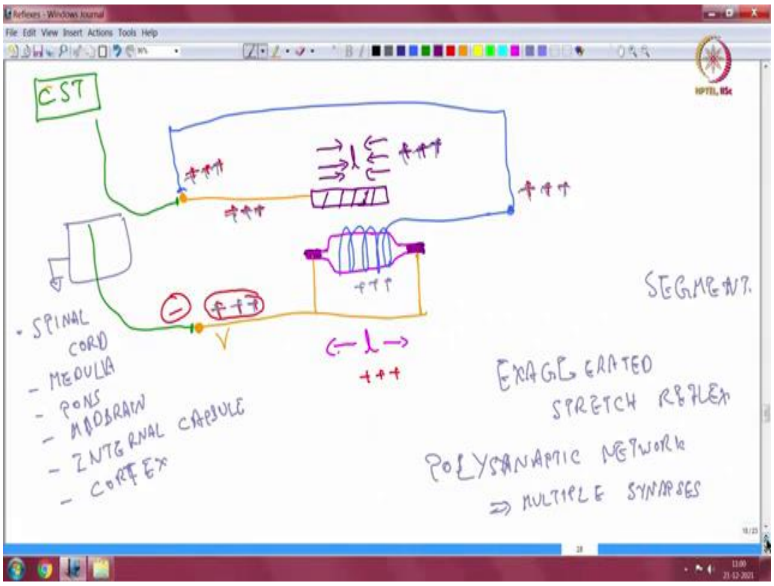

I have spoken about inverse stretch reflex which I had to introduce the concept of Golgi tendon.

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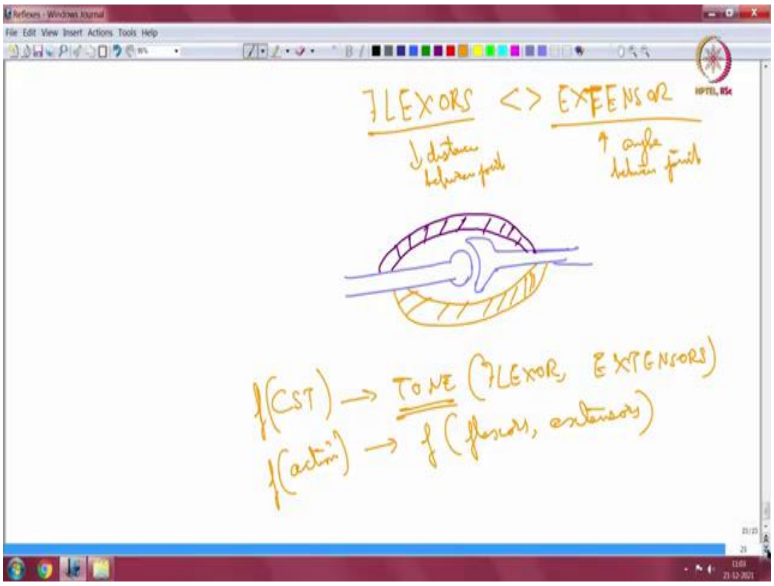

We now go to a next level of discussion, I need to introduce the terms flexors versus extensors. So, any joint, I am drawing a very simple joint for the purpose of understanding. For stability of the joint would require two kinds of muscles.

So, one muscle can be across here and another muscle can be across here, opposing set of muscles. So, many of the joints within the human body are not symmetrical, so there is this idea of flexors and extensors. So, flexors are something which reduce the distance between joints and increase angle actually. There is no distance as such so it is angle between joints.

So, these are opposing groups of muscle. So, we look next at the kind of dynamics which are necessary for the control of this system. Now, remember that tone is there for both flexors and extensors. So, it is common and this in turn is dependent upon corticospinal tract activation. So, function of corticospinal tract produces tone in both flexor and extensors.

Now, when you have actuation that is coming from action it would cause a change in both flexors and extensors. So, how do you do that? You can do it centrally or you can do it peripherally. So, the next part of the story is in the peripheral part of the network.

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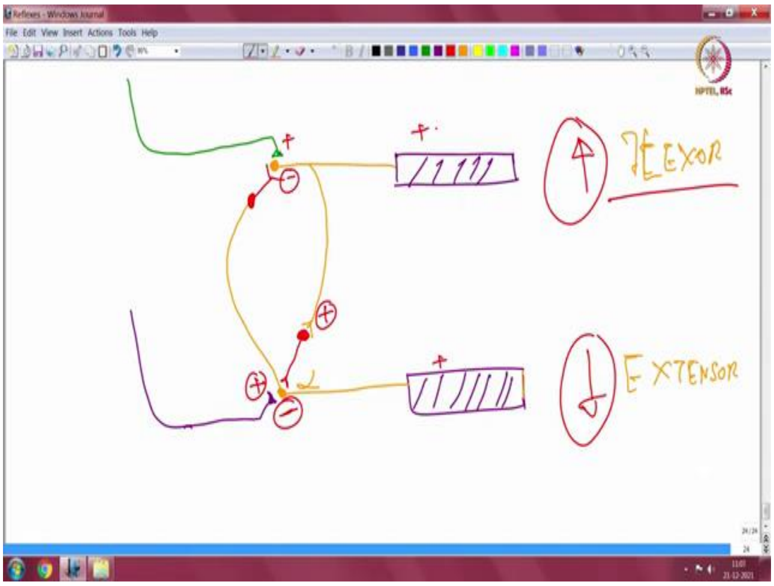

So, again draw one neuron for muscle, then this will be another neuron for the muscle. Remember that I am avoiding the Golgi, I am avoiding the spindle and all that stuff. So, this would be flexor, flexion extension.

So, most of your work is in the flexion part of the story, you hold things you release. So, writing you hold a pen. So, there is a lot of importance for the flexor part of the musculature. So, when there is an alpha motor neuron activation over here. It goes to the spinal cord and then there is another neuron which is negative over here and vice versa. So let us analyze this. So, we will have a circuit which is coming from above and let us decide that you have got a positive stimulus over here. So, positive stimulus causes positive stimulus here and that produces a positive stimulus parallel to this, but here it comes as negative.

So, what happens is when there is increased flexor activity there is decreased extensor activity now that is the sum of this discussion. So, you have networks, these are reflex arcs which span in a segment and which tell that when there is activity in some part of the musculature controlled by that segment.

The opposite set of muscles controlled in the same segment needs to come down because that is how you get purposeful moment. In contrary say for example, you want isometric contraction. So, you have a signal which is coming simultaneously.

So, what happens in that is you have signal coming from here to and this is getting stimulated, but this is getting inhibited and then you generate an equilibrium. So, I think in the previous thing we should have started with double plus. So, then you can have dynamic equilibrium of both flexors and extensors to hold a static position.

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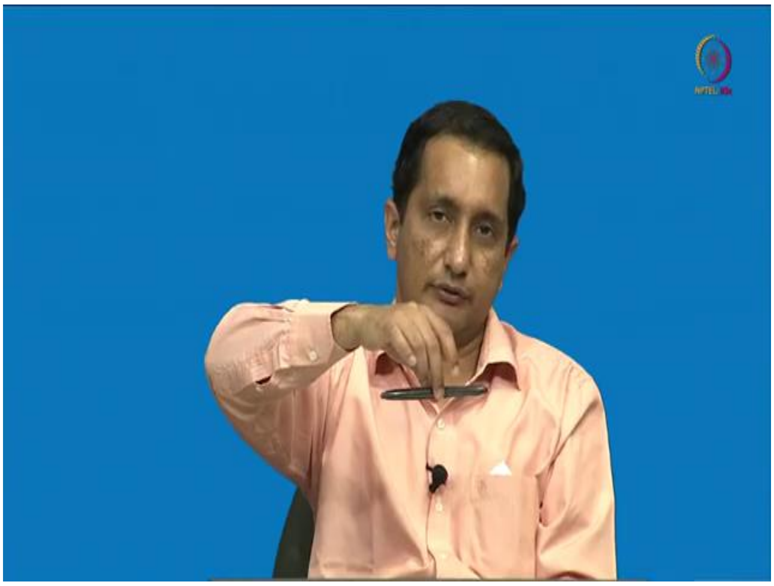

So, this would be an example of a static position, when both flexors and extensors are acting simultaneously for maintaining a given position of the object. So, these are local level reflexes. Then we can go one level above.

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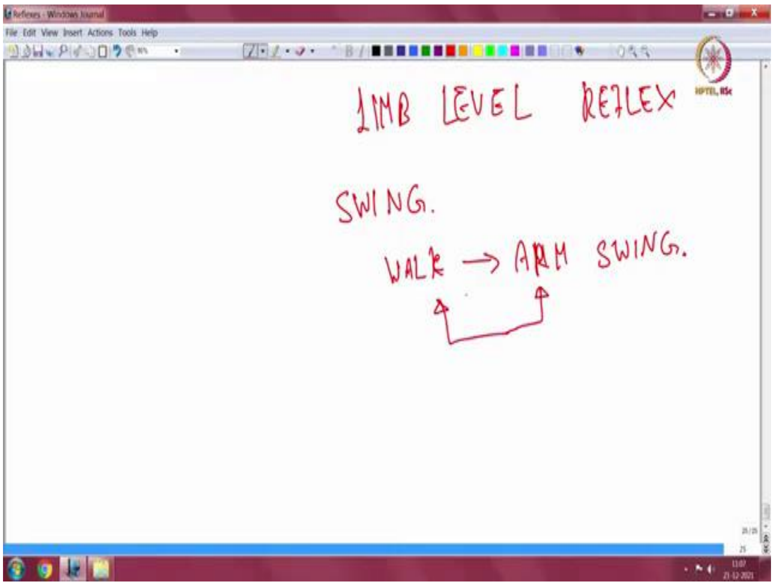

So, you can have limb level reflex mechanisms. So, the most common which I would like to tell is the swing. So, walking itself is a complex activity, but when you walk you have arm swing. And that is synchronized, you know it is linked and then you have synchronization happening between the upper limb set of muscles and the lower limb set of muscle.

So, large groups of muscles synchronize with other large groups of muscles to provide moment, they serve various purposes. Say for example, swing would sort of help in balance, it may be incidentally a network phenomenon which we have not yet understood.

So, there are several kinds of phenomena which are present which we attribute a particular cause but we may not be actually sure that these phenomena can be completely explained by these attributed causes.

So, swing for example, may be even related to the bipedal posture. So, when you are walking, arm swing may be a secondary activity which ensures that you have global stability of the entire body. So, it is not only limb level reflexes, but you even have you know more complex reflexes.

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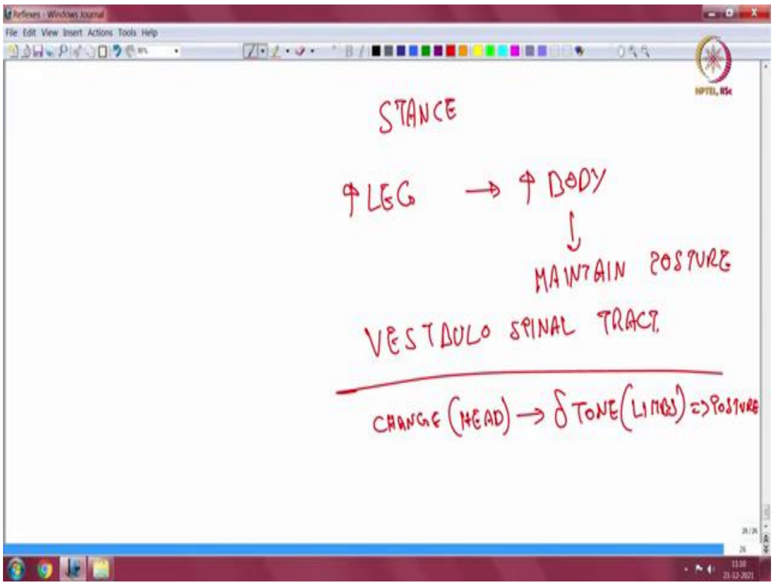

So, complex reflexes in terms of stands. So, when you stand on one leg the increased power on one leg would cause and increase on the tone on the opposite side body. So, that you do not lose posture.

Similar things happen in the head I think that I will discuss in some later classes to this vestibular reflexes. You remember that there is a vestibulo spinal tract. So, what is vestibulo spinal tract? It is any change in head, results in change in tone to change in tone of the limbs, this results in posture. So, you turn your head towards one side; bend your head towards one side. You need to have corresponding changes being made in your lower limb.

See head is free floating above your neck and head is pretty heavy. So, head is heavy and the bodies are bipedal. So, there are a lot of neural mechanisms, which are required to ensure that I do not fall off when my head is tilted to this side. So, some of them are mediated through the vestibulo spinal tract.

So, there are reflexes spanning multiple segments. So, we started at local reflexes, one group of muscle cells, one side of the body, one group of muscle cells. Then we started with monosynaptic, polysynaptic; polysynaptic on the same side we have flexors versus extensors.

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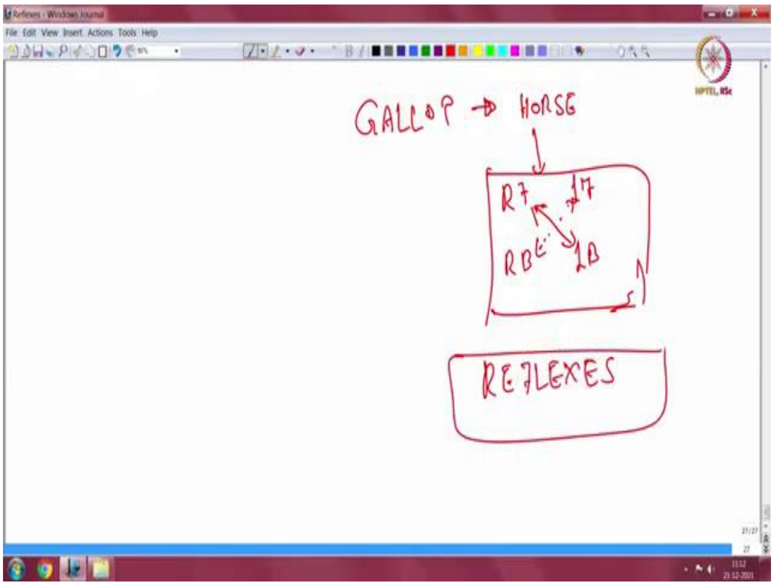

An interesting example of that would be the gallop of this I do not remember the class of animal. So, I will just use the term horse. So, horses gallop and the right front and left front, right behind and left behind. So, you have cross synchrony and that is how you have a gallop.

So, you have cross synchrony between opposing limbs for that function. So, bipedal of course, we do the same thing because if we do not have synchrony between the two legs you would not be able to walk or you would end up falling and that is incidentally manifestation of several DC states. So, these kinds of synchrony are manifested through reflexes.

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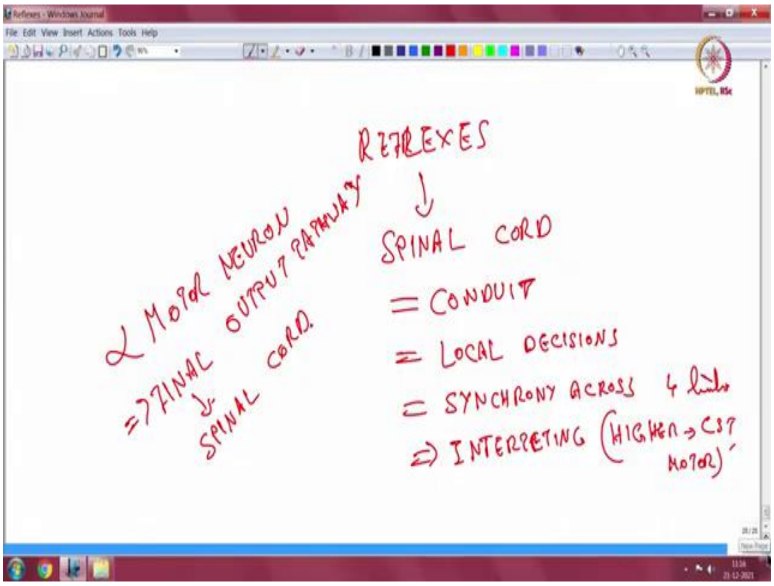

Now, at the end of this discussion I would like you to conclude that if you noticed that reflexes so far discussed are completely confined to this spinal cord. So, spinal cord is not just a conduit for messages which are generated with the brain, and which are transmitted to the other parts of the body.

It is also a place where local decisions are made. So, local decisions in the sense that you know you synchronize activity between two parts of the body and across 4 limbs, local decisions are made and synchrony across limbs 4 limbs for us.

So, these are the various functions which are carried out by the spinal cord. And they are very important, and they are responsible for what we call low level. Please do remember these are for anybody has seen spinal cord injuries and the manifestations of spinal cord injuries, you would understand the importance of the spinal cord.

So, far I have been talking only about the brain and its purpose and its way in which things have been going on in the brain. I highlight the spinal cord, role of the spinal cord at the end of the discussion of reflexes, these local reflexes and it is very obvious that how important a role the spinal cord has in one interpreting.

So, the other thing is interpreting higher signals. Higher in the sense corticospinal tract, motor cortex. So, it is the last part where the actual translation of the message, you know the neural messages which are generated in the frontal lobe goes to the motor cortex, goes to various parts of the brain and then comes out through various tracts from the cerebellum, basal ganglia, motor cortex. These signals all finally impinge on the motor neuron which is the final output pathway.

So, alpha motor neuron is the final output pathway, and it is present within the spinal cord. So, the functions of the spinal cord are the following. It maintains the local stuff, a lot of the local stuff is processed with in this spinal cord, lot of the decisions are made in the spinal cord, there it is independent of cortical activity, cortex does not bother to interfere with the work of the spinal cord beyond a certain limit. So, it actually modulates the function of the spinal cord.

So, the correct way of looking at it is you know all these are coded, you know they are functions implemented within the spinal cord. The cortex, just one changes the gain of these functions which I have shown you, the second chooses which of these functions are implemented.

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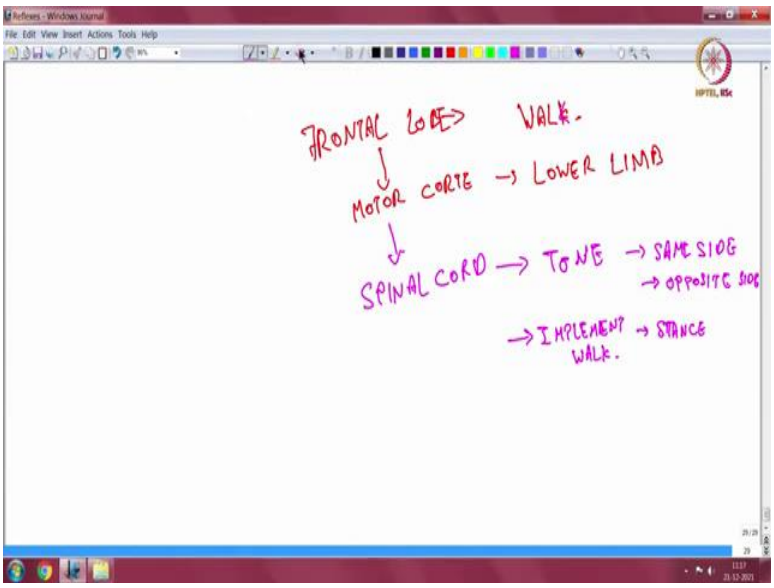

So, to give you an example the how the hierarchy would work is the frontal lobe generates walk that goes through the motor cortex. So, lower limb. So, that is just about the information which is there. So, lower limb is isolated for the purpose of walk.

But once that is generated then it goes to the spinal cord. So, spinal cord it does all, you know it is just walk over here, but it is low limb. Spinal cord would activate, it would change tone. Because you need to you know to prepare for walking and you have to do all those funny adjustments and tone to ensure that when you lift one of your legs you do not trip and fall.

So, it changes its tone. Same side and opposite side, you know I start walking from one side right. So, that is the point. So, same side, opposite side and then you implement the reflexes, implement walk.

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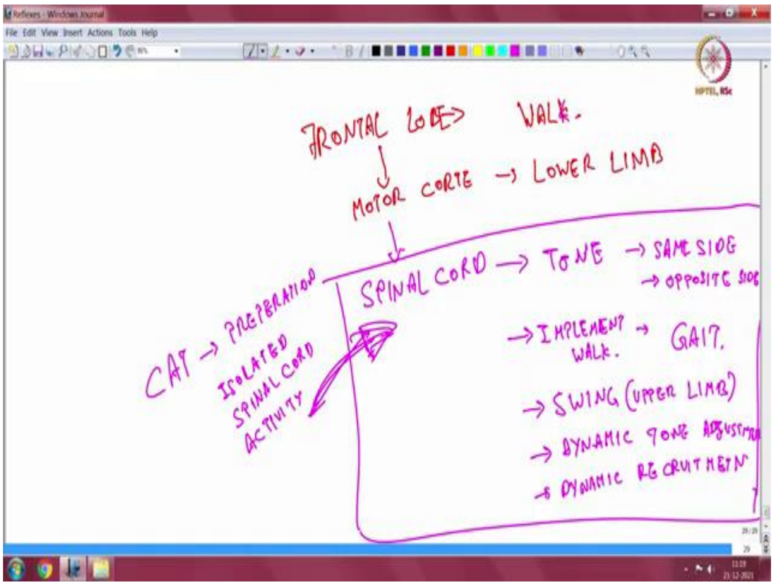

So, implements the gate function. Gate is walk and it also implements the swing in upper limb and it also processes local data. Say for example, you find that the surface is uneven.

So, there is this local in this one which dynamic tone adjustment. Walking on a flat area is very different from walking in a rough area. And you do not send that signals all the way up to the brain to make instantaneous decisions, spinal cord handles all of that. Adjustment and dynamic recruitment.

So, all of this is the function of the spinal cord, and it is independent of higher function. So, all of these have been demonstrated in CAT models. So, CAT as in the physical CAT not any other. So, CAT preparation they are called preparations. You can demonstrate isolated spinal cord activity which can be seen to demonstrably seen in all this all these kinds of function.

So, to summarize again it is a long way from the monosynaptic reflex, polysynaptic reflex, sets of very complementary receptor sensor mechanisms. So, these sensor mechanisms have different modes of acquisition. As I told for example, one is stretch in the muscle spindle, the Golgi tendon organ which also detects stretch.

Then there is proprioception which is again a method of stretch, and detects the angle between two joints and all these signals get integrated to form a rich feedback loop and that is actually responsible for movement. So, let me conclude this with a kind of a table kind of denotation and see how flexor extensor.

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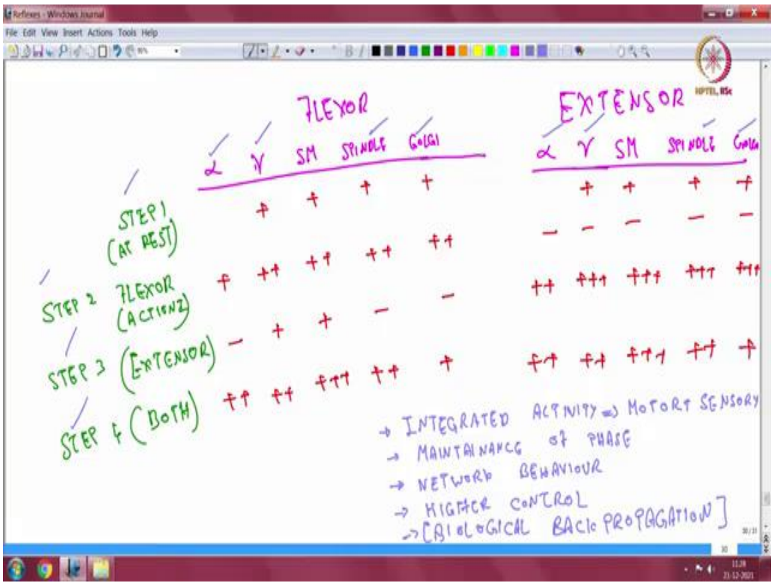

So, what all do we need? We need alpha, gamma motor neurons, skeletal muscle cell, spindle, then Golgi. So, alpha, gamma, skeletal muscle cells, spindle Golgi step one at rest. So, at rest you have some amount of gamma activity and that causes some effect in this skeletal muscle. There is some spindle activity because the gamma motor directly influences a spindle.

And there is some Golgi activity. It would be parallel because both of them are symmetric at activation. So, all these things are reflected over here. Now, we see what happens with flexor activity. So, flexor activity is action 1.

So, what happens with that is you have alpha which is increased, gamma which is also increased, skeletal muscle starts acting, spindles also start acting and then there is Golgi. On the contrary the alpha goes into negative, the gamma is sort of negative, skeletal muscle has to give way and the spindle signal comes down, Golgi signal also comes down. So, that is the kind extensor activity.

So, step 2, step 3 if you look at extensor activity this has to be suppressed. So, it goes into negative, so gamma comes down, skeletal muscle comes down, spindle comes down, Golgi comes down. You have extensor which is stepped up, extensor is generally a weaker muscle. That is why I am trying to include a bit of discrepancy into the power systems.

So, you need to step up extensor tone. So, that sort of increases the skeletal muscle increases a spindle and then you have this. So, step 4 both. So, this I would draw it like this. So, you have to increased gamma that in turn causes increased spindle; increased spindle that in turn causes increased alpha and that causes increased skeletal muscle.

Of course, there is increased Golgi tendon organ. Golgi to a lesser extent because you are maintaining a particular position. So, stretch as such would not happen. So, you can put in code to this whole stuff and try to model this for people who are interested in doing it. Very interesting exercise it would be.

There are features in this table which I would like to highlight. So, the first feature is integrated activity which implies motor plus sensory. What I mean? Motor, motor, motor, motor, sensory, sensory, sensory, sensory. So, that is integrated. Maintenance of phase. The cell activation has to be phased otherwise doing all these things simultaneously just does not work. So, you have to phase each of these activations which are there and network behaviour. Local networks, larger networks. Local networks within the muscle, larger networks across the spinal cord, flexor and extensor across.

And also, the idea of higher control is this. So, you know the higher control; what movement is to be done comes from top, but it gets implemented through this mechanism, so that is the idea which is conveyed. So, with this I think I complete a lot of this network analysis part of this spinal cord. How the network functions especially in terms of skeletal muscle which is the predominant output of the nervous system.

So, actuation through skeletal muscles is the way in which we interact with the environment, interact both in terms of acquiring further data and in implementing the will of the nervous system on the environment. So, there is no division. So, I am not spliting it into a motor system analysis and sensory system analysis, both of them are together.

I have highlighted various kinds of sensor systems. How they are built within the actuators, how they are associated with actuators and how the system is linked up with the actuating control mechanism. So, servomechanisms in brief have been described.

These servomechanisms are hyperlocal, local and distributed; distributed in the sense across upper part, upper limb, lower limb and things like that. So, these are brief glimpses into that. This is the limit of my knowledge, there are lot of stuff around which you can do that.

Why I highlighted the last table is for people who are in the programming field, you can actually implement this and this is the first introduction to computational neurobiology. I have been delving in slightly greater detail than this in the computational neurobiology introduction, but please to remember that computational neurobiology should also include the output dynamics which unfortunately is not being taken care off.

So, the output dynamics is what I showed over here and combination of output dynamics with the nervous system biology is what makes things. Even if you look at neural network designs the output is just used for back propagation.

In fact, what I have also highlighted over here is biological back propagation. So, biological back propagation is by this method. So, you have sensors which give feedback on the input systems and that is how you do the tweaking and will do differential. Change in alpha in time results in change in muscle length over time, causes another change in spindle over time again.

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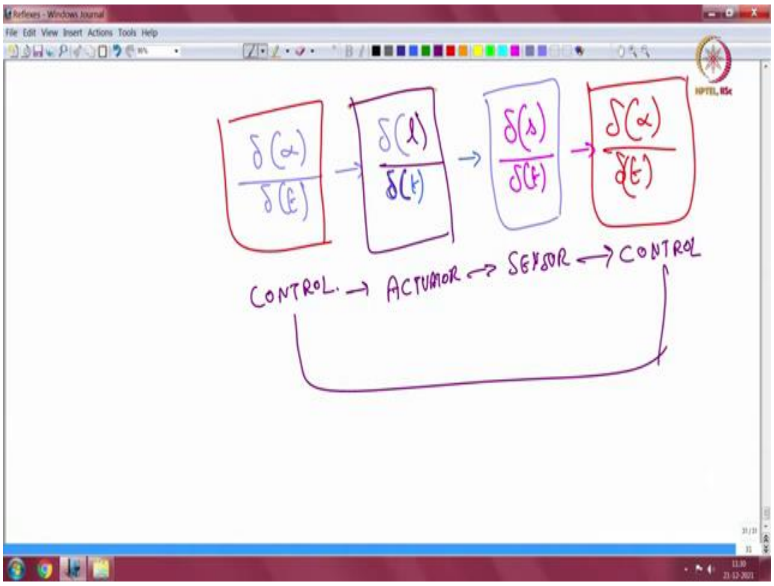

And that in turn causes change in alpha with time. It is a good start for modeling the nervous system. There are neuronal components, there are sensor components, there are actuator components, actuator sensor control and that is a loop.

So, you can depict the same stuff in terms of equations, and I think from here the people in CNNs and ANNs can utilize these equations to model this in whatever fashion. And it is a useful exercise for people who are used to coding, I think from here onwards it is easy to compile the stuff which I have discussed so far.

So, that is the point of showing this last thing, it is also a sort of introduction to the scope of computational neurobiology. So, these two pictures are to show case the scope of computational neurobiology.

Both in terms of the utility of using programming skills to depict nervous system function one. And to use concepts which have been which evolved in the nervous system to implement in programming techniques, and I mean programming techniques not programs.

So, that is the key thing. So, when I show this diagram, it is for the same intent. So, the idea that neural computation can be represented by elegant mathematical formulations which forms the first step of building computer programs to again depict neuronal function.

Also use concepts which are there within this instead of just using back propagation you have got many other elegant methods of generating output which can be inspired by the nervous system.

Thank you.