Neuroscience of Human Movement
Department of Multidisciplinary
Indian Institute of Technology, Madras

Lecture - 19
Motor Units - Part 1

So, welcome to this lecture on Motor Units as part of the course on Neuroscience of Human Movement.

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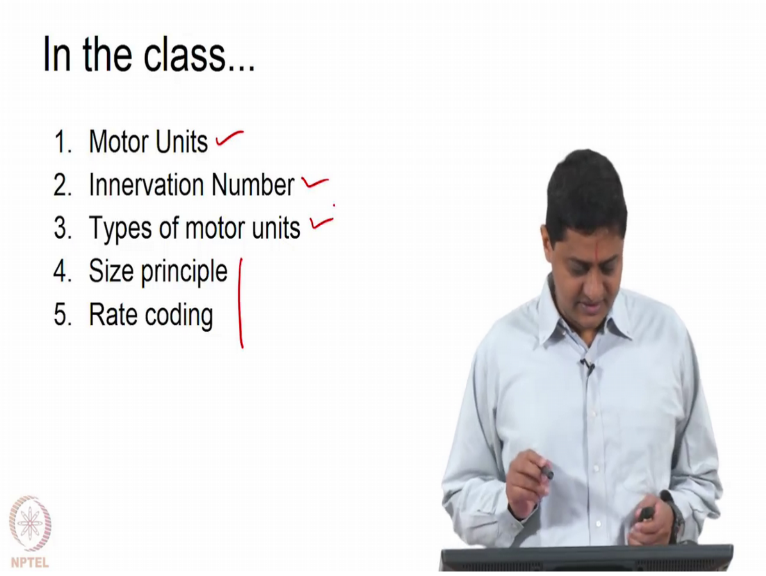

So, in today's class we will be talking about a motor units, innervation number and types of motor units and we will reserve these two topics size principle and rate coding probably for future classes. So, we will be focusing on these and the details related to these in today's class.

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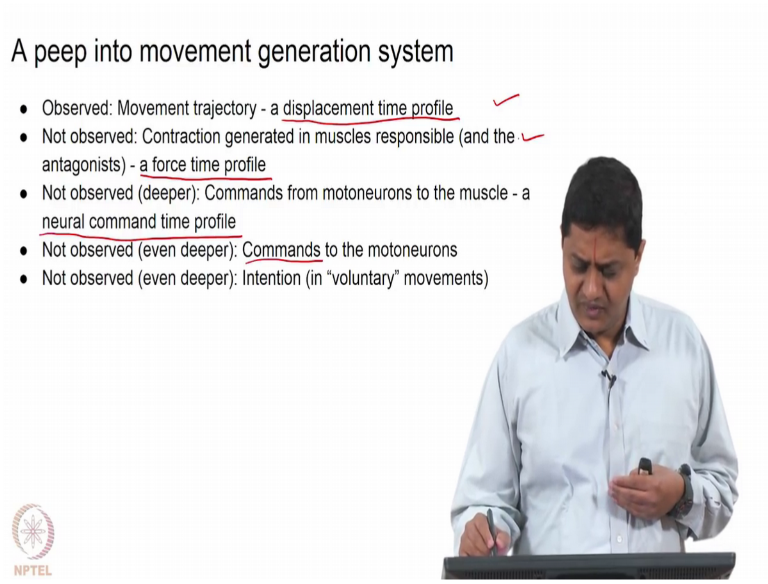

So, to remind ourselves what the problem under consideration is. What is the goal in this course? We are observing human movements. So, what is observed is usually a movement trajectory. I am making that movement so, you are observing this trajectory. So, the only observable output of the central nervous system are actions, are movements.

So, you are practically observing a displacement time profile. This is what you are observing, but how is this displacement time profile generated. Note that this displacement time profile is caused due to relative movement of bones. We saw in the earlier class that bones move relative to each other causing displacements what is observed as displacements bias, but this relative movement of bones is caused due to contraction of the muscles.

So, contraction is generated in the muscles responsible for those movements, but we also said that you know it is possible that if I want to have a smooth ending to a movement, I need to also produce contraction or activity in the antagonist muscle in the muscle that is producing the opposite action, so that I can have a smooth ending. So, what is produced, what is causing this time profile of displacement is basically time profile of contractions are muscle forces.

So, what is not observed is the time profile of forces produced by the muscle. This is not observable by us at least not without special instrumentation, so not readily observable. Secondly, how are these muscles controlled? The commands from motor neurons are passed on to the muscles. So, there must be if contraction is happening in some time profile, so there must be command time profile also give or take some time profile. Neural command time profile is generated from the motor neurons, but note that this motor neurons are located in the spinal cord. They must also be controlled somehow probably even at an even deeper level. They are probably controlled by some higher mechanisms or maybe some reflex mechanisms something else.

So, some commands to the motor neurons are also send that time profiles we do not know. So, these commands we do not know. Lastly what we do not know anything about is the intention if I am making this movement, if I am making that movement, you do not know why I am making that movement, what is the intention behind that. So, especially in voluntary movements, there are two classes of movements. We are going to call them as a reflex movements and voluntary movements. In voluntary movements, it is not clear what the intention is. By just observing the movement, you cannot say what the intention was at least.

So, there are lots of things that we do not know. So, we will be going deeper and deeper as the course proceeds, but where we are right now is approximately here and here. So, now we will be talking about what happens here in this stage and in this stage and how are these things working together to produce a movement. So, that is the goal for us just to remind ourselves. So, this is the peep into movement generation system.

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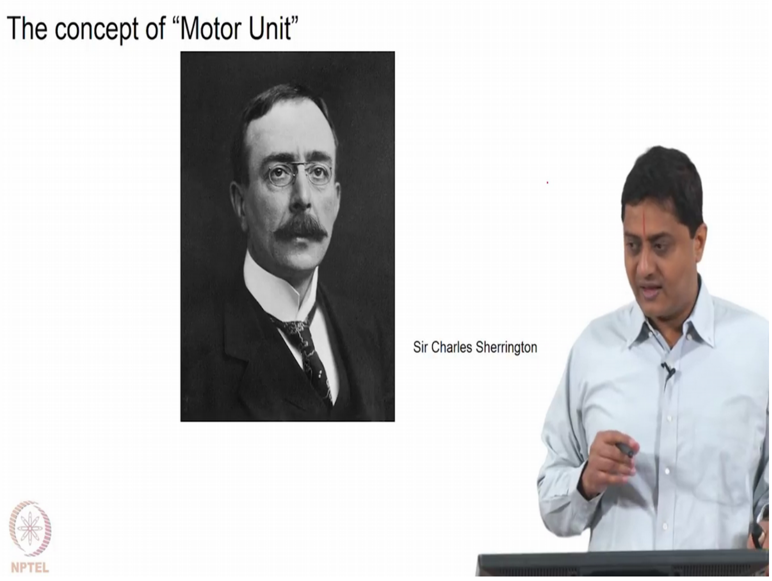

So, long ago about 100 years ago in 1925 Sir Charles Sherrington said that several motor neurons control muscle fibers in a particular fashion; what he said was that you know motor neurons control several muscle fibers attached to them, innervated by them. So, he called all the muscle fibers attached to a particular motor neuron as a motor unit. So, it was a revolutionary thought in the 1920's.

So, he said that one motor neuron and all the muscle fibers innervated by it together is called as a motor unit and because it turns out that whenever this motor neuron achieves action potential, whenever this motor neuron reaches threshold and produces an action potential, it also causes contraction in all the muscle fibers attached to it. So, that means if this motor neuron is activated, if this motor neuron is firing, that means all the muscle fibers will ultimately eventually produce force, ok.

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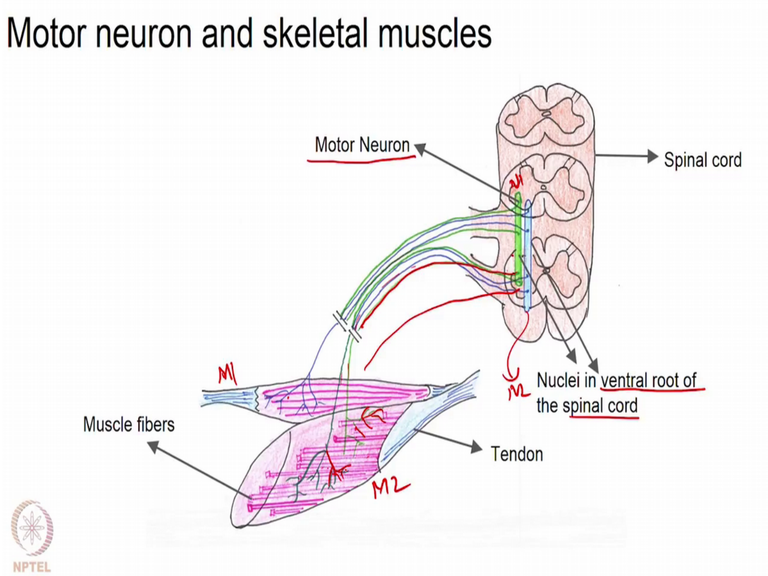

So, there are several things. So, the motor neurons themselves are located in the ventral root of the spinal cords. So, they are located in the ventral root ganglion on the spinal cord and they need, so for a given muscle. So, let us take this muscle for example, for a given muscle all the neuronal innervations need not come from the same motor neuron. It can come from multiple motor neurons. In other words, different nuclei can control different parts are different muscle fibers within the same muscle.

So, that means what you see here that there are some green lines coming here and then, there are some you know different colored lines coming here. They are coming from different nuclei distinct nuclei in the ventral side of the spinal cord. So, these neurons are called motor neurons. Why are they called motor neurons? We saw in previous classes why because they are responsible for production of movements, they are the once that release acetylcholine when there is an action potential. They release acetylcholine into this neuron muscular junction here; the neuron muscular junctions are all here.

Acetylcholine is released and when acetylcholine is released in this region, it causes an action potential in the muscle fibers. Why? Because we said the process we have repeated this multiple times due to the response of the anticholinergic receptors and sodium entering inside action potential is caused and then, there is excitation contraction coupling and eventually force is produced. Now, because they are responsible for movement generation, these neurons are called as motor neurons, ok.

So, different number of motor neutrons attach to muscles, so this may be more connections are not shown and also note from the same nuclei, they may attach to different muscle. So, here is one muscle, here is this is I am going to call this as say muscle 1, I am going to call this as say muscle 2, we are going to call the green one here as neuron 1 and the blue one here as neuron 2. Note there isn't any one to one relationship between M1 M2 and N1 N2. They both can attach to different muscles simultaneously. That does not mean that they will produce force in the same different muscles simultaneously. That is not necessary.

So, there is no exact one on one relationship. What is also true is that they exist. They exit from the spinal cord as a nerve in one bundle and then, as they get closer as they get closer to the muscle, what you see here he said there is branching. You see branching happening here and branch and sufficient number of branches happen here and they innervate multiple number of muscle fibers and it turns out there is all not necessarily any topographical arrangement of motor unit versus muscle fiber. In other words, usually in the usual case muscle fibers innervated by different motor units are found to be neighbors to each other.

So, if one muscle fiber is contracting, there is no necessity. It is neighbors are you know also contracting. That is not necessary because it is possible that its neighbors are innervated by a different motor unit and that motor neuron is not fire. A muscle fiber is going to contract if and only if its boss or the motor neuron associated with it produces an action potential. At other times, it is not going to contract or it is not going to produce an action potential.

So, the neighboring muscle fibers may belong to different motor units, that is 1 2 is that the number of muscle fibers attached to a motor unit varies. It need not be the same, right. So, it can be very high, it can be very small and depending on that the properties will change.

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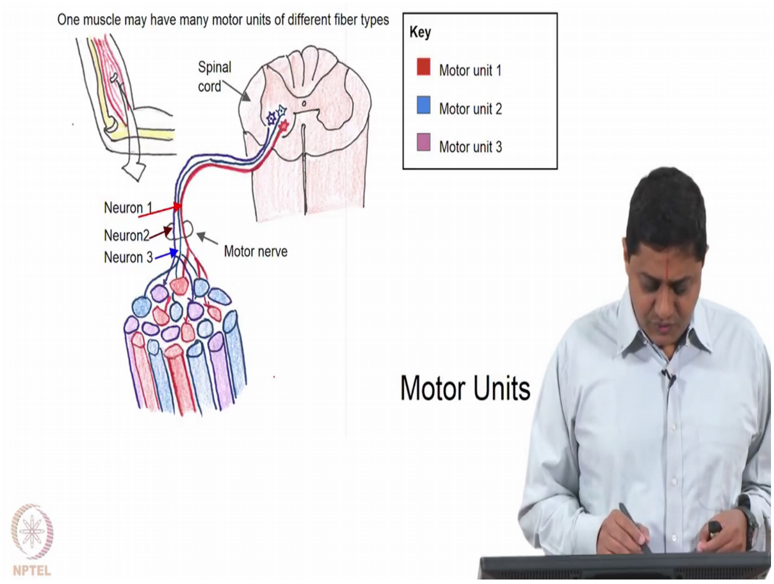

So, we will continue to see that. So, what you see here is another example of the situation. So, there is neuron 1 that is here and that is innervating. You see different regions in the muscle bundle and there is neuron 2 that is attaching that is mixing in with. So, this is neuron 2 here. So, that is mixing in with what is already innervated by neuron and there is neuron 3 which is second mixing.

So, if neuron 1 alone where to fiber, what would happen is that only those fibers will contact its neighbors, not necessarily contract unless its neighbor is also innervated by the same motor unit or it is also possible that both neuron 1 and neuron 2 are firing. In that case, its neighbors may also contract and so on and so forth. So, to remind ourselves a motor unit is composed of a motor neuron and all the muscle fibers innervated by it. One motor neuron can innervate multiple muscle fibers, however if you take a muscle fiber, it is going to be innervated, but only by one motor unit one motor neuron.

So, that means that one to many relation between motor neuron and muscle fibers at given muscle fiber, this is informational command from only one motor neurons. So, whenever that motor neuron is giving the command, the response by the muscle fiber is obligatory. It does not have the response; it does not have the power to say no I am not going to contract. Sorry I have a, I am receiving conflicting commands. No, there is only a single commander for a muscle fiber from the muscle fiber point of view.

For each muscle fiber, there is only 1 motor neuron that is commanding it, but 1 motor neuron can command multiple muscle fiber simultaneously and whenever it fires, all the muscle fibers are attached to it. Also fire this is comparable to the situation in the class today. Now, you are all here. I am teaching to all of you I can be considered to be the motor neuron and you are all you know taking in some sense say a lesson from here or a command from me. So, that means that I am the teacher and there are like 10 of you here, approximately 10 of you here. All of you receive command only from me, but I can teach to 10 of you. So, that is the relationship. Of course, the relationship is obligatory in the muscles sense.

So, whenever I give an assignment, you must do it. If it is a graded assignment, you do not have the choice of not doing it. It is that response is obligatory or the neuromuscular junction or the neuromuscular synapse is an obligated synapse. Every time the motor neuron fires, the muscle fiber must fire. If it does not fire, then it is a disease pizza and listed the diseases of the neuromuscular junction in the previous class.

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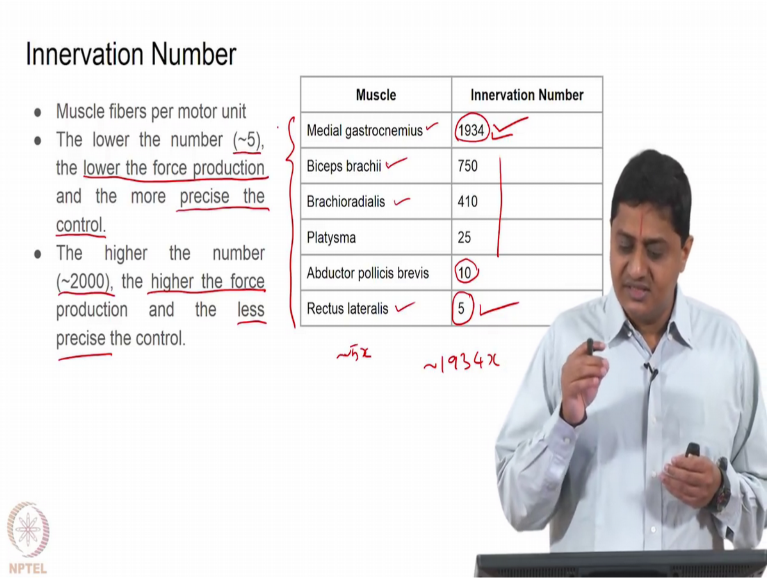

So, what else we said that different number of muscle fibers maybe innervated by a motor neuron, this number can vary between as small as 5 to as high as 2000. So, what is a re what does what does this mean if you assume that all muscle fibers produce approximately the same force. This is a wrong assumption. In reality this is not true. Different muscle fibers produce different amounts of force, but for the purpose of this discussion alone, let us assume that any given muscle fiber under consideration for the purpose of this class alone produces the same force.

Then, if I have a motor neuron that innervates five muscle fibers say x amount of force is produced by each muscle fiber, then I have a particular case where the innervation number can be as small as 5. That mean 5 muscle fibers are innervated by a single motor neuron and when that motor neurons firing how much force is going to be produced 5 x. It is not because O said x amount of x Newton or x milli Newton force is going to be produced by a muscle fiber. Of course, I am assuming all muscle fibers produce equal force.

For the purpose of discussion, this is not true and it is also possible that this number may vary. It can be 10 or in the big muscles of the leg, it can be as high as 1900 or approximately 2000 in that case. So, what will be the force that will be produced? That will be 1934 x. So, it is possible to vary the amount of force produced by choosing the right motor unit, right motor neuron.

If you choose a motor neuron that is connected only to 5 muscle fibers, the total force that is going to be produced will be approximately 5 x. Actually, this is not exactly equal to 5 x. This will be approximately 5 x. Why? Because all the muscle fibers attached to motor neuron reach action potential at approximately the same time and they undergo excitation contraction coupling at approximately the same time.

So, that means for the forces to some we said that the circomiar force production when we discuss a circomiar production, we said that forces are summed in series within myofibril and in parallel across myofibril, this is what we said. So, within a fiber if force has to be added across multiple fibers, then there has to be phase agreement or in some sense they all have to produce force at approximately the same time if the forces are in or not in sync or they are out of phase. Then, it is possible that the forces may not sum the time at which it reaches is only approximately the same. So, the force summation is also only approximately true. So, this 5 x and 1034 x is approximately true.

So, in general why have this arrangement that is a question. Why? Because it is necessary for me from time to time to, produce forces with precise control. There are reuse, there are times when we as humans need to manipulate objects with precise control. This is the case of say for example manipulating an object finger or hand held objects say I am writing with the pen, I am writing with this pen and I am marking things here and I am circling things here. Things like that involve precise control of forces with my fingers. So, that means I am more interested in the fineness of control. So, in such cases I am going to use motor neurons that innervate a smaller number of fibers or there are cases when I need to produce a relatively large amount of force. For example, when I am standing even during quite standing, so when I am understanding my body weight is supported by the muscles responsible for posture maintenance.

So, although it might appear like you know standing is a passive activity, it is not. There must be some forces that must be produced to ensure that you know I do not fall down. So, posture is maintained by active processes or when I am walking or when I am jogging or when I am say running or sprinting, in such cases the amount of force that needs to be produced increases tremendously. Sometimes an amount of force that needs to be produced can be several thousands of Newton's.

So, there are cases when I need to produce few Newton's or less than a Newton amount of force to manipulate objects with the fingertips and there are cases when I need to produce several thousands of Newton's or kilo Newton's of forces from time to time. These are distributed of course. These are in different limbs. So, I am talking about hands and legs, but there are different cases. So, when I need to produce a large amount of force I will I could choose this motor unit that produces that amount of force. In general the higher the innervation numbers which is approximately 2000, the higher is the force, but that also considered the cast the control is less. I cannot control this very precisely. If I am saying I need very precise control, the amount of force produced is going to be small.

So, there is a compromise, there is a trade off. Is it possible for me to have both? The answer is yes. It turns out that there are at these are only two extremes that are also cases with medium or intermediate innervation numbers. Note I am talking about inner I am taking innervation numbers from different muscles here. This is medial gastrocnemius, this is bicep brachioradialis, this is a rectus lateralis. So, these are different muscles. These are not the same muscle, however even within the same muscle, you are going to have a distribution of innervation numbers. You are having innervation numbers ranging from relatively small to a relatively large numbers.

So, about 20 to 50 motor neurons innervate a muscle and their ranges can be as small as the amount of force produced by a given motor unit can be as small as 5 percent of the total force that is produced can be as high as 70 percent or can be as the volume of muscle fibers occupied by the fibers innervated by 1 motor neuron can be as high as sometimes as high as 75 percent. So, this means that there is a variability between muscles, this is between muscle case. There is also a variability of the innervation number within the muscle. So, if I take one muscle, this innervation number can starts from a small number can be very large. Let us take an example.

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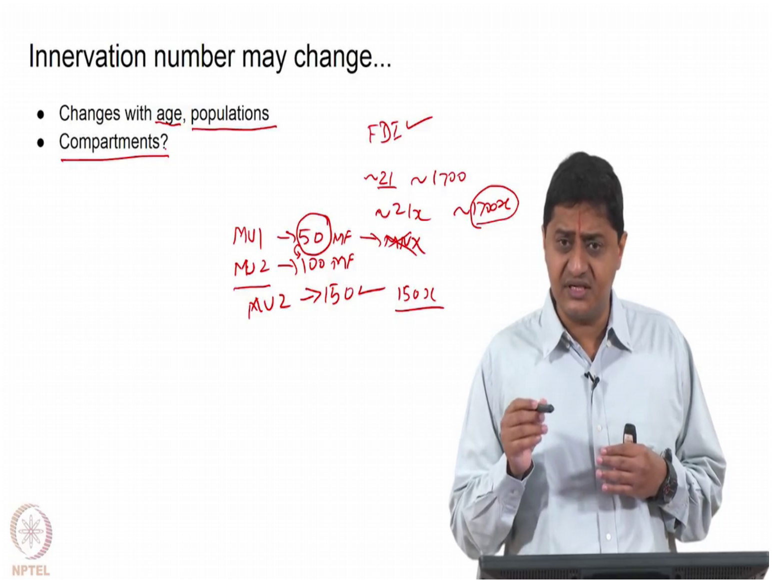

So, innervation number may change. Let us take the example of say like this example since it is related to our research. What we do the first dorsal interosseous muscles are what we call us FDI. This muscle is responsible for producing that action, right. So, for that movement this muscle is responsible. What are the innervation ratios associated with this? This can be between innervation number can be between approximately 20 to approximately 1,700.

So, again if I assume that x milli Newton of force or x Newton x units of force is produced by a muscle fiber and all muscle fibers have equal amount of force producing capability, in that case the motor unit associated with 21 innervation number is going to produce approximately 21 x and this is going to produce approximately 1,700 x. There is great variability in the amount of force. So, the greatest force that is produced, that can be produced by a motor unit in the first dorsal interosseous muscle can be as high as the average force produced by a leg muscle. Let us say that one more time, so that it is not confusing.

The greatest force, the maximum force that can be produced by the finger muscle by the first dorsal interosseous finger muscle can be as high as the average force, not the greatest force, the average force produced by some leg muscles. So, that means it could give you an idea of the strength that of these muscles and of its force producing capabilities and note what else also happens innervation number changes which with age and it changes as a function of populations. What do I mean by populations? Health and disease as a function of disease, as a function of exercise, as a function of the type of exercise, etcetera.

So, what happens with the age for example, what happens with age is some motor neurons simply die with age. As a person gets older, some motor neurons die and what happens to the muscle fibers innervated by them, all the muscle fibers innervated by that motor neuron are often for a brief amount of time. So, for a brief amount of time, these motor neurons are funds. They do not have a bust. After sometime the motor neurons, the newborn motor neurons develop new branches and innervated. These are fund muscle fibers. So, these muscle fibers that for earlier part of a different motor unit are now part of a new motor unit.

Now, let us consider the situation with a bit more rigorous to see what happens. So, earlier they were part of motor unit 1, ok. Let us say then the number of, for the sake of discussion let us say that the number of muscle fibers in motor unit 1 was approximately 50, ok. Motor unit 2 initially had say 100 muscle fibers, ok. Now, this motor neuron is dead; this motor neuron is dead. So, it is not functional. So, these 50 have become are funds. They get attached or they are innervated by this motor neuron or M1 2.

So, what will then be the innervation number for the motor unit 2? Motor unit 2 will have a new innervation number of 150. How does these change things? Anybody can guess how does this changes things. Earlier I was able to produce if each of the muscle fibers producing x milli Newton of force, then earlier I was able to produce forces as small as 100 x. Now, I am going to be able to produce 150 and 50 x. This might be viewed as good. That is good. So, as we get older I am going to produce a greater amount of force.

Now, what happens is that as you get older, your ability to produce fine forces reduces and no longer able to produce fine forces which is the reason you observe older people when they are grasping objects or when they are walking, their body is stiffer. They usually produce larger amount of force, then the physics require it to produce certain amount of force as you get older, the amount of force produced is much greater than what the physics demand. That means, that it is energetically inefficient. I am producing more force than needed; my body is stiffer than needed.

So, it also changes, occurs populations. We will discuss this in future slides or in future classes and also, what else happens is I said earlier that there are in the usual case that different muscle fibers or neighboring muscle fibers need not belong to the same motor unit, but in some special cases it turns out that a given muscle has a specialized compartments, what are called as compartments. These compartments are innervated by a different groups of motor neurons that are selectively innervated depending on that are selectively activated depending on the task at hand. If this is the task that I want to perform a specific compartment is activated. If a task to be performed is different, then a different compartment is activated

Now, this rise of the question what is a muscle a morphological unit in some sense, is it a geometrical or some construct that is purely morphological or is it functional? This debate continuous in the area of musculoskeletal bio mechanics b this is not get into that, but there are also cases let us just note that there are also cases where muscles function in compartments. The best example is once again the muscles associated with the hand function.

So, these are called the extrinsic muscles of the hand that have long tendons going and attaching to different fingers. There they are all present, they are housed in the forum, but the force produced on the fingers, they have relatively long tendons that go through this. These muscles are, it has been shown that these muscles have compartments and they are activated depending on which finger needs to be activated which is the reason in humans especially we are having relatively more independent finger movements when compared with other animals usually and this also changes.

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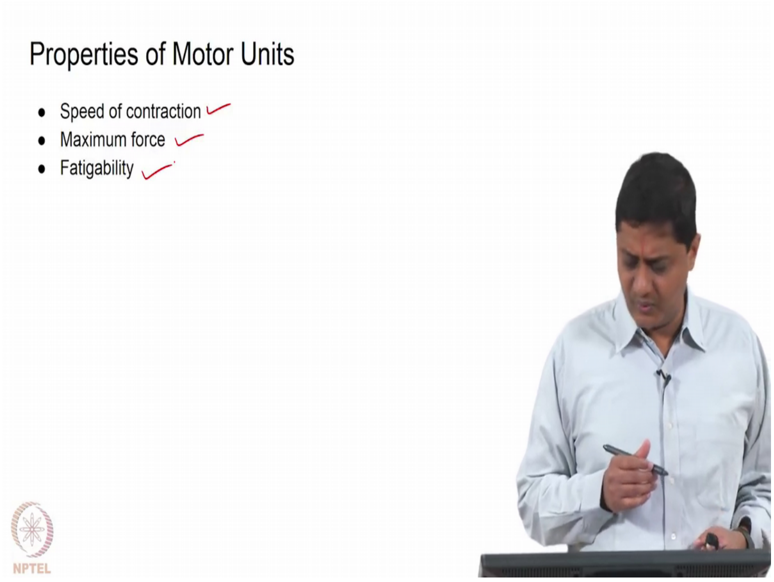

So, those are different properties of motor units. These properties are the speed of contraction. The maximum force that can be produced by a motor unit and the fertility of this, there are some correlations between these properties. We will see them one by one we said in the previous class.

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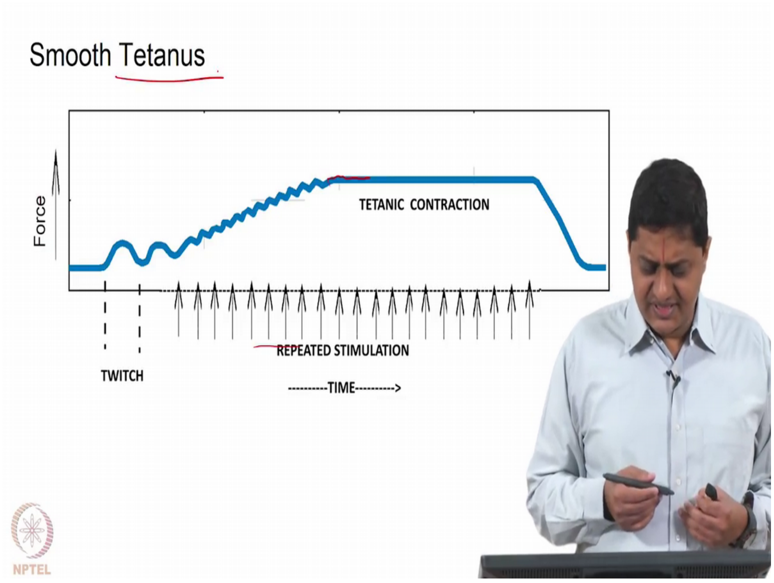

What is which force? So, one stimulus is arriving force is produced and if another stimulus is arriving before this stimulus could relax. The force acts up and keeps on adding up like that. If the stimulus train is fast enough such as that if the stimulus train is fast enough, such as that it produces relatively smooth and constant, what is appreciably constant when compared with the previous cases. We call that as the smooth tetanus are titanic contraction. Now, a question is what frequencies should I activate to produce a given force or what are the speeds at which I should activate, what are the frequencies that are associated with it, what are the maximum force that I can produce ? These are the questions.

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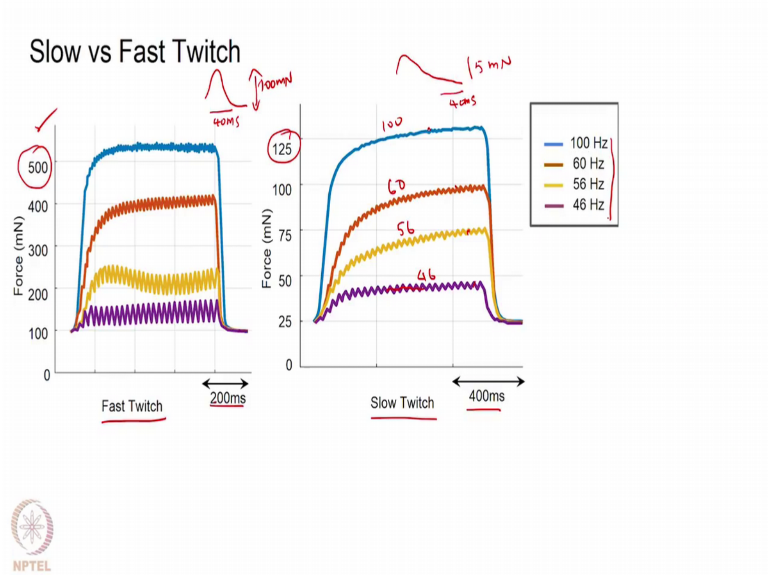

It turns out that different types of motor units and muscle fibers are present. So, in the case of there are two cases, two extreme cases. We will consider two extreme cases. Let us consider the case of the fast twitch. In this case, it turns out that the first produced is something say about 100 milli Newton say for example, that takes that produce in about say 30 to 40 say about 40 milliseconds. In this slow twitch case, similar for a slightly different force profile is produced. This is 40 milliseconds, however the amount of force produced is of the order of few milli Newton’s.

So, that means the fast twitch fibers can produce relatively large amounts of forces in relatively brief periods, but the slow twitch fibers produce small amounts of forces, ok. Also note the scales here. So, this is about 125 milli Newton’s produced by these fibers and this is about 500 milli Newton’s that are produced by this fibers. So, as the frequency of firing increases, one would see as the frequency firing increases from 46 to 50-60 to 100.

So, as the frequency of firing increases, what you see is that the force increases. So, as the frequency increases, the force increases. There is a relatively good agreement in that. This is 46, this is 56, this is 60 and this is like 100, ok. That is all that is true and also in the fast twitch fibers. So, this is in the case of slow twitch. This is also true in the fast twitch fibers except that the force produces much greater. It is about 500 milli Newton; here it is about 100. So, the scales are different. Also the time scale is different here. This is 400 millisecond; this is 200 millisecond.

So, that amount of force in the fast twitch fiber is produced in a smaller amount of time. This smaller amount of force is produced in a greater amount of time. So, that means these are two extreme cases we have taken and we have obviously have conveniently taken the two extreme cases that are required. There are cases in between. Let us consider where these would be useful. Are there times when I would like to produce relatively small amounts of forces for relatively long periods of time? The answer is yes.

This is the case of endurance sports. For example, I need to produce small or relatively sustained amounts of force or a stained amount of activation for to finish running several of kilometers in the case of a marathon for example. So, it is not expected and it would not be fair to expect for us the muscle structure and the control and the training method between and endurance athlete between a marathon runner and say a sprinter, between Usain Bolt who is a sprinter, he runs 100 meters in less than 10 seconds.

So, if he is running 100 meters in less than 10 seconds, what are the arts that this person is actually going to be able to complete a marathon. The truth is that this person will find it very difficult to complete a marathon despite the fact that he is actually a Olympic level sprinter. He is suited for this sort of explosive force production. He has more of these motor units, those motor units that produce large amount of force in relatively brief periods of time, the training, the composition.

What is the best composition? Actually the best thing is a mix of two. So, in real life there are going to be situations where you are demanded to produce relatively small amounts of forces for relative long periods of time, relatively large amounts of forces for relatively small periods of time and everything in between there are going to be cases when you are going to need an intermediate amount of force to be produced for an intermediate amount of time.

So, healthy mix of all these things are required. The point here is that you know there are these two extreme cases that in which these motor units can come in and this varies as a function of stimulation frequencies, this varies as a function of motor unit properties and what else?

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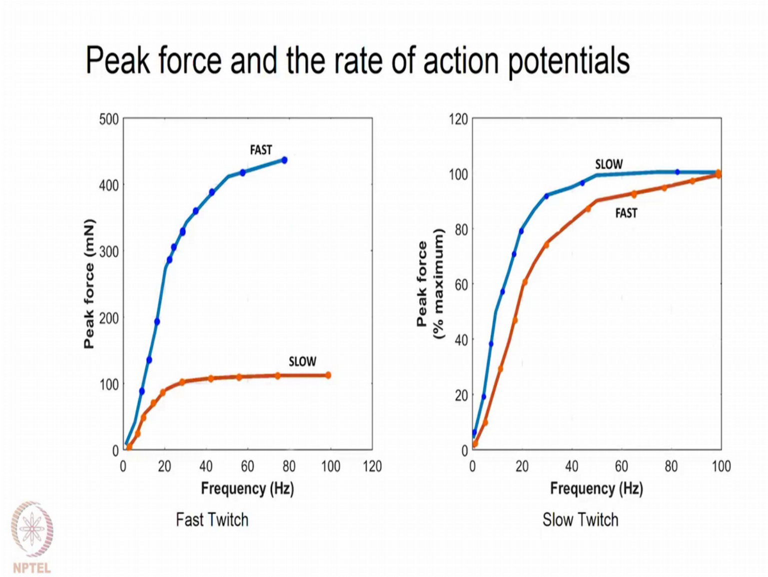

The peak force that is produced is a function of stimulation frequency we said that. So, in the case of fast motor unit if you take what happens is that as we increase the frequency, the amount of force that is produced increases in a very high to a very high level. It can be as high as 400 to 500 milli Newton's, but that does not happen in a slow motor unit. So, in a slow motor unit after sometime this curves accurate and that happens at about 100 to 125 milli Newton's.

Even as I keep increasing the frequency of firing, even as I keep increasing the stimulation frequency, the output is not going to be greatly increased in the slow case, but is going to greatly increase in the fast case. Here the colors are mixed up. Here we are calling the blue colour slow and the red color as fast, but not the difference. This is peak force, absolute peak force here. The y axis is normalized by the maximum peak force.

What does this tell us is, this is the percentage of maximum of peak force that can be produced by a given motor unit. So, if I keep stimulating, what happens is the motor unit that is responsible for that is slow and the motor unit that is fast reach at different rates and they will peak out at a particular frequency. They will reach at a particular frequency. Note the difference is what is the difference is, two are probably produce these two curves. This curve and this curve are produced probably from the same data, yet you are going to have a difference in what is slow in what is first which curve is appearing on top and which curve is appearing in the bottom. The reason is we are normalizing it by the maximum force that is produced.

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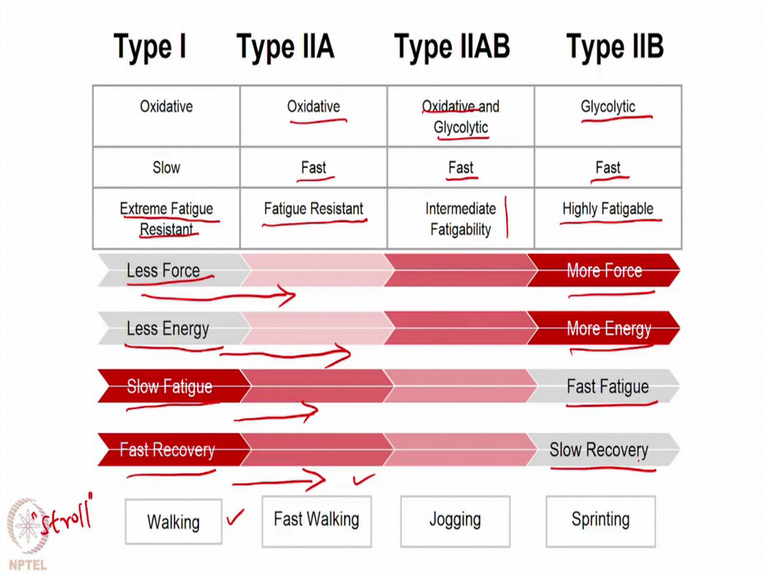

We said there are different types of, this we classified only 2, but actually there are more than 2. Those cases that are those units that are slow that are oxidative. These are extremely fatigue resistant, they produce very small amounts of force and they consume less amount of energy. The chance of them getting fatigue is very small and they recover very fast from fatigue. These are the motor units that are recruited, these are the fibers that are recruited during walking say for example, and then, if I say I am interested in brisk walking, faster walking, there is a difference, there is a gradation. You are taking a stroll like that is a nice beautiful campus here.

So, I just taking a walk just saying the natural, enjoying a natural beauty without focusing on the velocity of your walk or in other words, you are taking a stroll not shown here. You are taking a stroll relatively slow walking, then walking or I am interested in brisk walking. Walking is this case where I am not running or what is the difference between walking and running? There is a particular point at which in running that there are going to be tension. Both your feet are going to be off the air and during walking, there is going to be at least one foot not clear which foot is at least one foot is going to be on the ground. Is it not simple differentiation? So, I am going to, I am doing fast walking, but not running. In that case, I will be recruiting more of this type which is going to produce relatively fast. They are relatively fast, they are still fatigue resistant and then, I am jogging. In this case, I am actually engaging in running, but relatively slow running. In that case that is going to be a mix of oxidative processes and glycolytic processes.

So, there is going to be a mix of aerobic respiration and anaerobic respiration. There is going to be fast units that are recruited and these fibers are of intermediate fatigability. The amount of force produced varies, right keeps increasing in that direction, the amount of energy expended keeps increasing in that direction. The chance of fatigue keeps increasing in that direction. The chance of recovery keeps decreasing in that direction. As I am proceeding from slow to fast, the chance of recovery from fatigue reduces. The chance that I am going to get fatigued increases, goes up and the chance that I am you know spending more energy and producing more force increases and I can keep doing this.

I can sprint if a person is sprinting or engaging in or weight lifting or doing something like that, in such cases the process is purely anaerobic. It does not involve aerobic process, it does not involve oxidative processes, it only recruits fast fibers and it is highly fatigable. I cannot lift 100 kg mass and keep it and sustain it for a very long time. Nobody can do that. First of all, I cannot lift 100 kg weight, but let us say that you know I am able to lift it and it is not like I am going to be able to do that in for a very long time. We saw in previous classes that I am also not going to be able to lift it very quickly. I can lift a relatively light object very fast that is relationship between velocity and force requirement.

Here in this case I cannot keep lifting it and have it for a very long time because this is I am going to be recruiting highly fatigable units. So, I am going to get fatigue very soon. So, that means more force although there is a need for me to produce more force, more energy is expanding. They are going to fatigue fast and the chance that then going to recovery is relatively slow.

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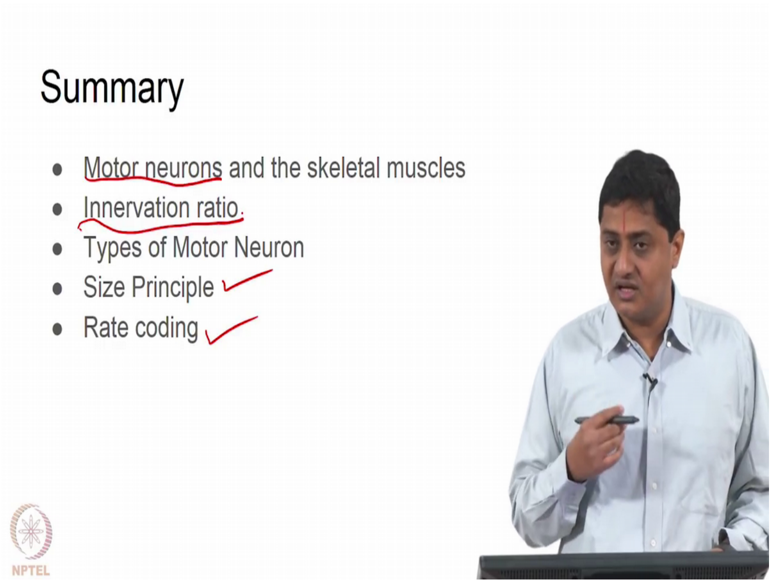

So, we will stop here. What we need to see in future classes are Size Principal, Rate Coding and the implications of size principle and rate coding for control of movement and so on and so forth. We also will to discuss other things concerning motor unit function, such as electromyography and how to process electromyography signals, ok.

So, what we have seen in today's class is motor neurons, types of motor neurons and motor units, the types of motor units and the importance of innervation ratio, how that affects function and how different ranges or different classes of type 1, type 2 etcetera classes of units are fibers can lead to different function. So, with this we come to the end of this class.

Thank you very much.