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

Lecture – 15
Skeletal Muscles – Part 2

So, welcome to this class on Neuroscience of Human Movement. In this class, we will talking about human Skeletal Muscles, this is Part 2 of our discussion on skeletal muscles.

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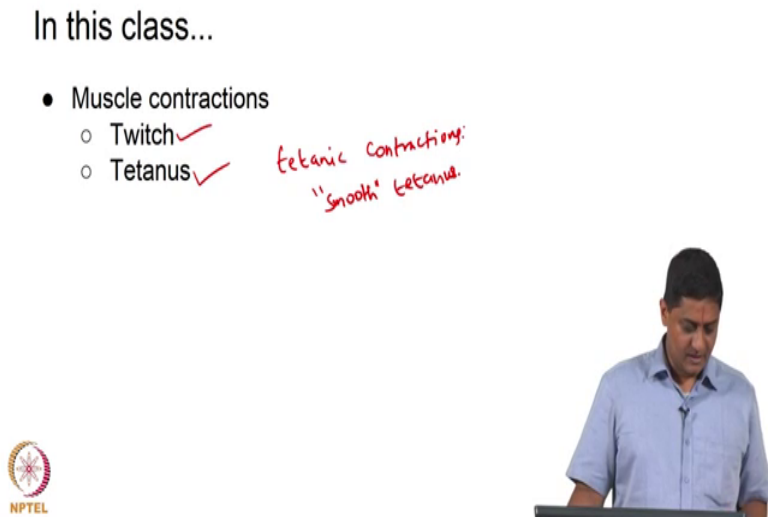

So, in this class we will be talking about types of contractions; Twitch contractions and Tetanic contractions also called as a smooth tetanus. So, this is also called a tetanic contractions or smooth tetanus. So, essentially each contraction is not necessarily smooth, but when multiple contractions add up it makes the overall output to be smooth. How does this happen is a part of today's class.

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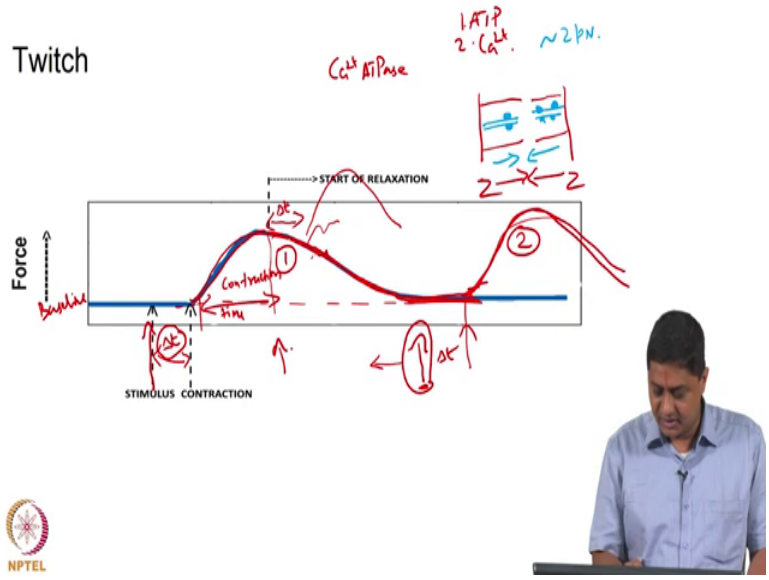

So, let us look at what happens when a single action potential arrives at neuromuscular junction. When a single action potential arrives at the neuromuscular junction and it causes a single action potential in the postsynaptic muscle fiber; say for example, one action potential at the neuronal end causes one action potential at the muscle fiber and this reaches say the T-tubule and through the interaction of DHP receptors and the ryanodine receptors, calcium is released and this causes release of. So, this action potential when it reaches the T tubules to interaction of DHP receptors and ryanodine receptors calcium is released and this release of calcium somehow causes the contraction and this can happen only in the presence of ATP.

So, there are 2 essential things for a muscle to contact or a sarcomere contact, these are ATP and calcium ions right. This is the situation. Now if single action potential arrives at the neuronal end and reaches the muscle fiber and reaches the T tubule terminal cisternae then some amount of calcium is released.

This presence of calcium is sufficient to move the troponin in the troponin tropomyosin complex in such a way that actin and myosin can done interact right, that causes an increase in force; let us remember how then happens. How then happens is the myosin attaches to the binding sites and actin and then pulls in such a way that the z, suppose this is one z disc and this is another z disc and suppose thin filaments are in red, the thin filaments are in red.

For example, if this is the case, this distance become shorter and a small amount of force on the order of the order of about 2 piconewtons is produced, we saw this. Now, suppose for the calcium is depleted; suppose the action potential arrival has stopped then what happens? The calcium is taken from the intracellular matrix to the sarcoplasmic reticulum through an active process called as calcium ATP's, we saw this in the previous class. Is it not?

So, then calcium is taken back what happens there is no more calcium that is available to continue the cross bridge cycles, look the cross bridge cycle is going to continue as long as both energy in the form of ATP and calcium are present. As long as calcium and energy are present there is going to continued contraction and continued interaction of actin and myosin that is going to happen until and unless calcium withdrawn right.

So, when the action potential is not there then what happens? The ryanodine receptors close and then the calcium ATP's continues to pump the calcium from the intracellular matrix of the muscle to the sarcoplasmic reticulum, once again within the muscle; it is a storage house we also saw how that is getting stored due to the presence of the special protein calsequestrin right we saw this.

So, when calcium is getting depleted then what happens? Sarcomeres are no longer able to produce force are continue the cross bridge cycle, then that leads to a reduction in force. Of course, this is a physical and physiological process; it is not like once the calcium is withdrawn the force will immediately come down to 0, there is no instantaneous drop in the force as one would expect that is not what happens. This is slowly getting withdrawn right because there is an active process that is pushing calcium inside the sarcoplasmic reticulum. As that is happening there is slow withdrawal of force and then it comes down.

Obviously, this depends on 2 things there are 2 things that dictate whether the force level will sustain or whether it can increase? What are the various things that could affect this? An important point is how long does it take for the force to be developed right? This is called as the contraction time. So, this varies between fibers, between muscles, between individuals, this can be with a lot of practice trained to be shorter, etcetera right.

So, the contraction time is something that dictate for how long is it going to take for the fiber or for the sarcomere to develop the force. Now, if suppose another action potential

arrives here before the contraction time has been elapsed, then it is possible for you to either sustain the force or to continue developing the force, but in the particular case that we are now discussing another action potential has not arrived, this is not there; so, this action potential that a true is not there.

So, then what happens? Since there is only one action potential that has arrived enough calcium has been released due to that action potential, then calcium ATPase is continuing to do it job. Then what happens? The force continues to decline and then reach the original rest state approximately. So, one is the contraction time, the other is the arrival of action potential before the contraction time elapses.

Suppose, there is a stimulus of the action potential is given here until the next stimulus is given say there. Then what happens? Then there is going to be a small gap, note between the stimulus arrival at the neuronal end and the development of contraction there is a small delta t time that elapses that also elapses in this case and then there will be a development of force. What causes this delta t? Let us remind ourselves. When we are talking about the stimulus, we are talking about an electrical event, we are talking about an ionic event, is it not? Whereas, contraction is referring to a mechanical event.

In general in these cases the mechanical event is preceded by the electrical event. First the stimulus arrives and then the actual force production or the actual displacement or the actual reduction in sarcomere length are the distance between the z disk, just for clarity I am going to draw it like this. The actual reduction in z disk follows the electrical event ok. So, because this is a physical phenomenon there needs to be some time that needs to elapse and also the interaction the release of calcium and the interaction of troponin, tropomyosin all these things take some non zero time, some time it takes for these reactions to happen for this chemical reactions to happen then cause the mechanical event ok.

So, as I said if the next stimulus is arriving at that point then the next contraction will be developing here. It is not possible for this contraction, this is contraction 2 and this is contraction 1, it is not possible for the contraction 1 and contraction 2 to interact because there is some non zero time, during which the forces gone back to the initial force to some baseline force level this need not be 0; for practical purposes, we can assume this force to be 0, but this need not exactly be 0 right.

So, if for example, I move this stimulus a little bit to the left say for example, to here. Then what happens? The force will start developing after again there will be a delta t time that will be required for development of force again here, here there is already some force these could add up. So, in twitch contractions you have development of force and then drop of force.

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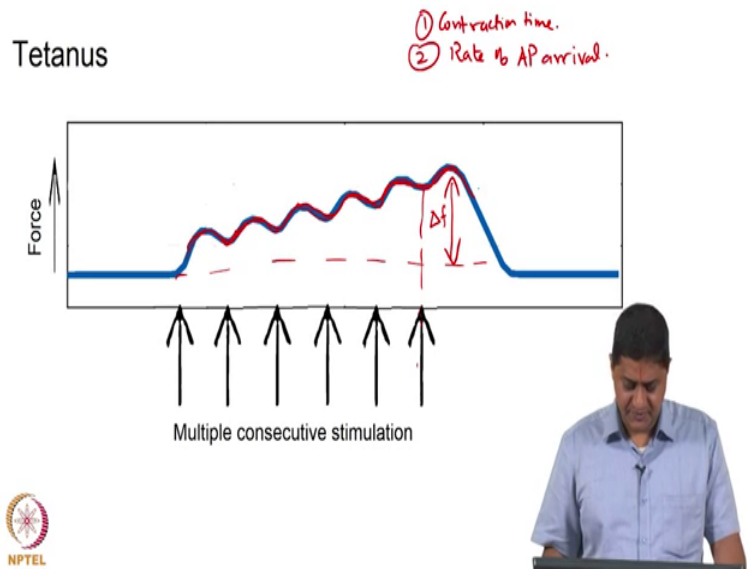

But before the force drops if another stimulus arrives then it is possible for the new force to get added to the previous force. Of course, this depends on 2 important factors, one is contraction time; this is unique maybe for each sarcomere or at least for each myofibril. So, this varies between muscles, this varies between people, this varies between groups of individuals, this varies as a function of ace, this varies as a function of disease, etcetera right.

Second is the rate of action potentials. So, if action potentials are arriving very fast then there is going to be a greater chance that 2 force levels are going to sum up right. If they are coming sufficiently farther in time right, if the 2 action potential are farther away in time, then what happens? One action potential force cannot be increased beyond the original twitch related force level right.

So, both of these are crucial. So, suppose in this case there are multiple consecutive action potentials arriving and they are sufficiently close in time then the before the this twitch can go back to 0, the other twitch has arrived and that causes an increase in the

first level and before that could died on another action potential has arrived and that causes another twitch etcetera. Thus essentially by the end of this as in some delta t after the arrival of the last action potential you are having essentially that much force developed, so much is the increase in the force level right. Now how to maintain that how to do that? That is the question.

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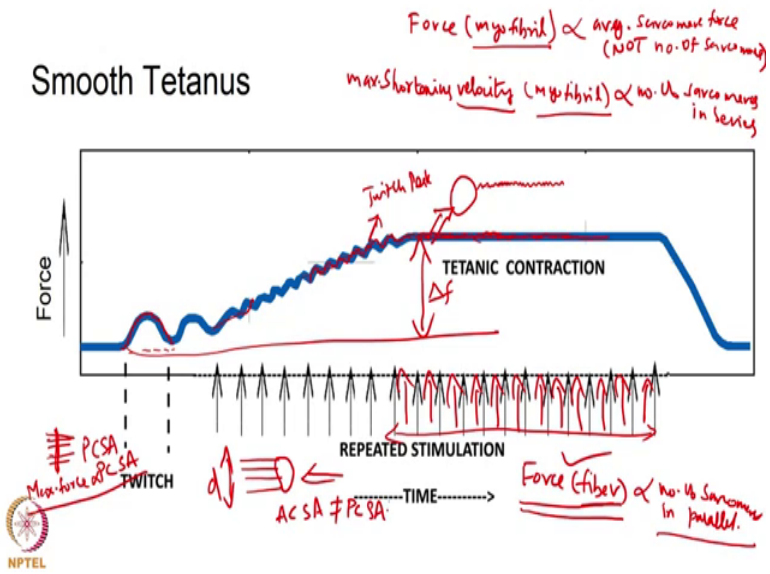

It turns out then if for example, then I keep increasing the stimulation frequency to a much higher value say for example, like that much higher value right. Then what happens essentially is this force level is reached and then it is maintained. Actually if you zoom in if you zoom in what you will see is, small variations in forces at that level also, but depending on the resolution of the drawing it might appear to be constant, there are going to be small variability there is going to be some variability here. Note that the blips in the tetanus here even just below the tetanic contraction here are due to the peaks of twitch peak right.

Essentially here also this may be due to twitch. For this to happened you need a sufficiently large frequency, sufficiently high frequency right of a stimulation; at that level you are going to have tetanic contraction, below that level you are going to have an increase in force, much below that level you are going to have a twitch and then drop in force to approximately the baseline level ok. So, once again here after the titanic contraction is developed what you are having is a force level that is higher by some delta

f above the baseline level ok, the force produced by the fiber or by the fibril by one myofibril right.

One myofibril is composed of multiple sarcomeres in series whereas, one fiber is composed of multiple myofibrils in parallel this is what we have seen in the previous class right. So, there are several things that are of interest, one is force that is produced by a myofibril, force of a myofibril, turns out that the force of a myofibril is proportional to the average is proportional to the average sarcomere force, but not the number of sarcomeres.

So, having a large number of sarcomeres does not increase the force, but having sarcomeres that can produce a higher average force will increase the force, so, it is important to note the difference right. However, if you have a relatively large number of sarcomeres in series in myofibrils, in a different myofibril you have a relatively small number of sarcomeres a question is; what is advantage of having a larger number of sarcomeres in a muscle fiber? It turns out that the maximal shortening velocity, velocity means in this case not velocity of movement in this case we are talking about velocity of shortening, time rate of change of contraction displacement not the actual movement related displacement.

So, now when I am moving my arm that is movement related displacement and there is a velocity of movement. Here when I refer to this velocity I am referring to contraction velocity right, it turns out that the maximum shortening velocity of a myofibril is proportional to number of sarcomeres. So, having a number of sarcomeres having a higher number of sarcomeres has an important positive consequence, then you can develop the force at higher rate you can develop it quickly enough right.

So, that depends on the number of sarcomeres, but not the force level itself; very important distinguish the 2 alright. And then the other point is what about the force that is produced by a fiber? Please note here I have been talking about myofibril, here I am talking about fiber; when I am talking about fiber I am referring to several myofibrils in parallel, is it not?

This is proportional to the number of sarcomere not in series, here this is in series, here this is the force produced by a fiber is proportion number of sarcomeres in parallel ok. So that means, if I had a larger number of sarcomeres in parallel essentially what does that

mean? That means, the diameter this is looking at it from that dimension muscle size itself, is it not? So, as the diameter of the muscle increases you are going to have larger force.

Actually there are other details such as what particular area are you referring to? This is a detail that we will discuss in future classes. However, I will just briefly touch upon that. Suppose there are multiple fibers, if I find a cross sectional area that is perpendicular to each of the fibers like that if I find an cross sectional area like that, that area is called as Physiological Cross Sectional Area or PCSA and it turns out that the max force produced by a muscle is proportional to physiological cross sectional area, that also is in agreement with this principle that we just now discuss.

So, basically the physiological cross sectional area refers to the area due to the number of fibers as in the area that is perpendicular that is found orthogonal by cutting the by making a cut orthogonal to the direction of movement, direction of the fibers themselves right. Now, that is also similar to finding the number of sarcomers in parallel, is it not? So, then you have maximum force that is proportional to the physiological cross sectional area, this is a known fact and that agrees with this fact that we have seen right.

So, there is different cross sectional area that is discuss by mechanics that is what is called as the anatomical cross sectional area, it turns out that this is different from the physiological cross sectional area, I will leave the details for a future class or interested readers can actually check that in future.

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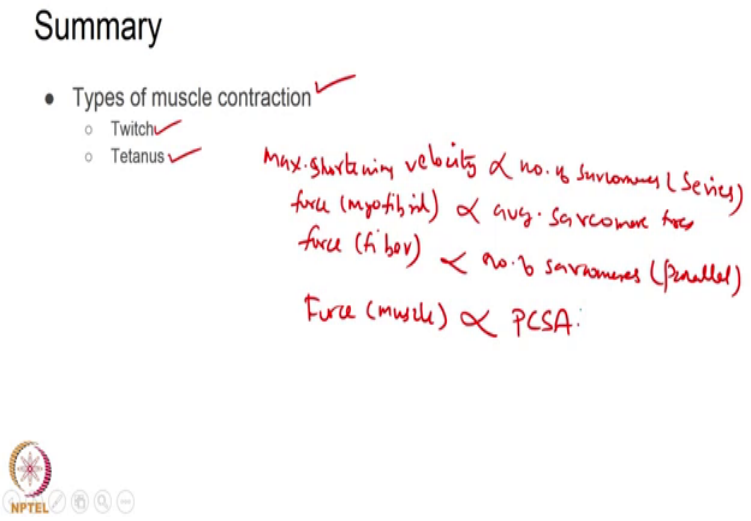

With this, we come to the end of this class. So, in summary we have seen types of muscle contraction, we have seen twitch, we have seen smooth tetanus and we also seen details about what causes maximum shortening velocity and what causes force of a myofibril as in what influences that and what influences force in a fiber, etcetera right.

So, this is a proportional to number of sarcomeres in series. Force of myofibril is actually proportional to the average sarcomere force not the number of sarcomere, whereas, force of a fiber itself is proportional to number of sarcomeres not in series, but in parallel. Of course, force of a muscle is proportional to the physiological cross sectional area, this is a detailed that needs to be studied in future classes. So, with this we come to the end of this lecture.

Thank you very much for your attention.