Compliant Mechanisms: Principles and Design
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Lecture - 70
Compliant tissue cutting mechanism

Hello, we are going to discuss a 4th case study in the course today and this lecture is about a compliant mechanism used for tissue cutting and the new feature that compliant mechanism offers here is a way of passively limit in the cutting force of the device. So, we look at how a compliant mechanism can be used in applications where you want to cut tissues safely, by putting an upper limit on the cutting force.

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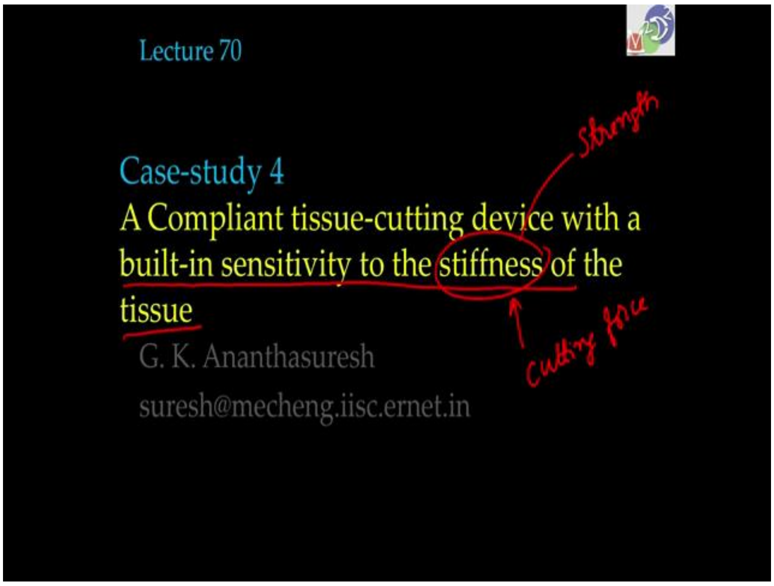

So, we have now A compliant device, that has a built in sensitivity to the stiffness of the tissue, when you say stiffness it is also related to the cutting force you can say stiffness or strength also. So, stiffness or we can think of this as strength; so, we look at how we can do it using again compliant design; that is what you illustrate in this case study.

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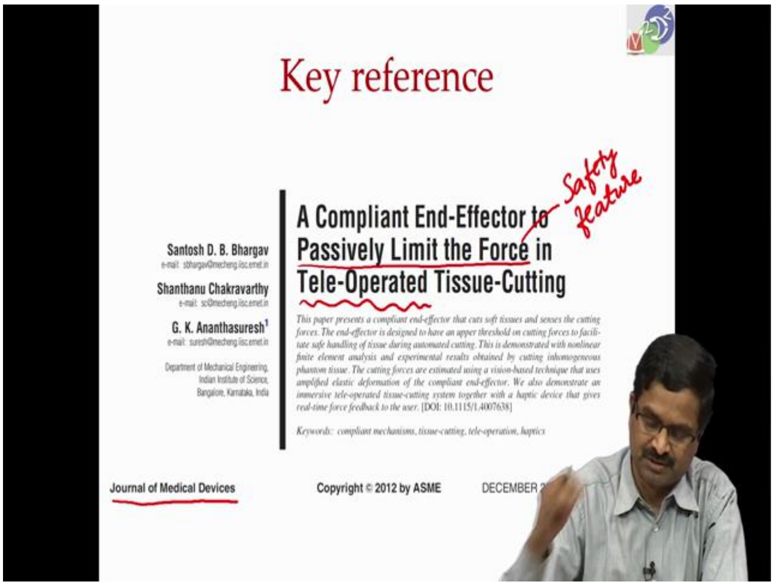

The key reference for this is this paper that appeared in journal of medical devices. So, compliant mechanisms have a number of biomedical applications, this is one of the examples; volume 6 in 2012. As you can see this also have other features which is other than passively limiting the force that is one feature this is a safety feature. So, we have a device that ensures that when you are cutting something it could be tissue or something else that it will not apply force more than sub value that we set. So, the mechanism is designed for that purpose.

So, other feature is this Tele-Operated tissue cutting; that is you have master slave mode. So, whenever you do Tele-Operation for cutting purposes, you need to have a way of sensing forces. So, here a compliant mechanism is also used for sensing forces. So, there are 2 features one is an upper threshold on a cutting force other is sensing of forces.

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This is the setup that we have developed. So, here is compliant end effector and there is some phantom tissue that it clearly go for real tissue is a phantom tissue that we can make ourselves and there is a master here that is my student applying displacement to move something and the slave device here which cause the tissue.

So, in between we can say there is a geographical device; even though it is in the same lab it could be one location in the world that could be another location and these 2 are connected through the internet. So, when holding the haptic robot here what you have is a haptic robot is there, this is the phantom device haptic robot. The movement of the hand here is communicated to the slave device and the slave device moves; as the slave device moves the cutting force on the phantom tissue is measured and that goes here.

So, what goes from here to here if you say the input from here to here is going to be with position information. So, the motion of the hand is related to the slave device and then from this to the user comes the force feedback. So, it is a close loop system Tele-Operation, we can cut something while sensing the force. So, that is normally done that is not anything new; what is new in what I am going to talk about is this cutting force is limited passively not by control limited passively to a certain values, so that you can cut things that take less than certain value of the force, other thing is just we would not cut into the tracks by itself.

So, there is a built in kind of a intelligence in the device that will make you safely cut something with only that much force the device that we have has a cutting force about 2 Newtons, more than that it would not cut it simply comes back by itself there is no control. So, a good design usually tries to eliminate the need for control and here is an example of a design which has passive control built into it, not active control where you have a controller and actuator, a control input and all that you do not have all this, just normal device that ensures this safety by using a compliant mechanism.

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So, here is again the compliant end effector is indicated; compliant end effector. So, the compliant end effector that we have is encased this box here. So, you do not see of much that, you will have to see later what you see here is the scalpel. So, there is little (Refer Time: 05:53) sharp thing here that is what is going to cut the tissue, that is attached to a compliant mechanism that we will discuss and there is a camera the Siemens camera, that looks at the displacement of this scalpel and based on that we estimate the force and knowing the force the user can cut or not the Tele-Operation, but more than that there is an upper threshold on this where the force or cutting force exceeds that value, the scalpel will simply retract.

So, imagine that there is an a cutting blade you are cutting and it could be Tele-Operation otherwise if you hold to this compliant mechanism, where these scalpel attached as you are cutting, when the force of cutting exceeds certain value it simply of cutting exceeds certain value if simply will retract. So, if there is a specimen here is simply will retract that is what we will see here.

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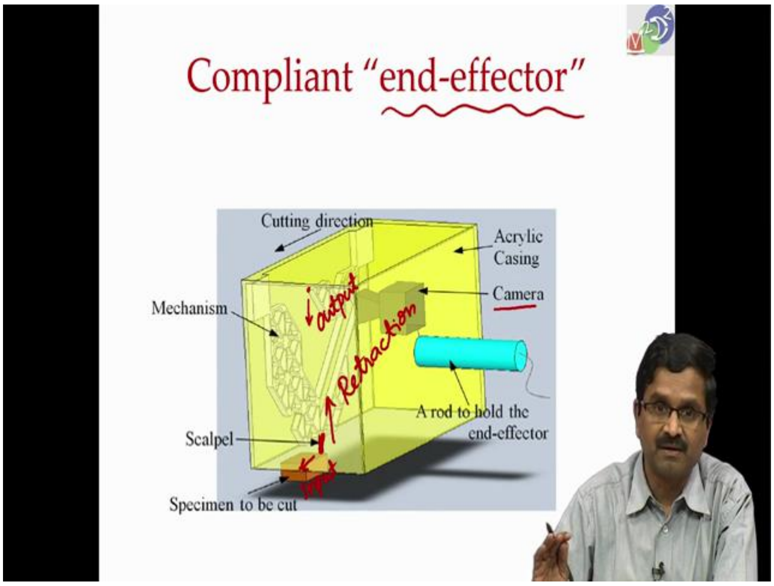

So, here is the end effector of the thing. So, the specimen to be cut is here, the scalpel is attached to the compliant mechanism; this is the knife edge that cuts here. So, we have the compliant mechanism and there is a camera looking at this point. So, as that compliant mechanism as this while casing is moved this (Refer Time: 07:23) casing in which that mechanism enclosed is moved, this is the direction of cutting.

When you are cutting there will be some force, because of the force applied here or felt over here this point will move. So, this will be the input here and this will be the output. So, this movement is seen through this camera and there is a computational model of the compliant mechanism from which we know the force applied over here. So, we have model the mechanism if we know the displacement here and here are just the camera is looking at this displacement, we can estimate what is the force is. Once you know the force you can do the Tele-Operation by giving force pin back to the user who is at a remote location.

Another thing this mechanism has interesting feature, that when the cutting force exceed certain value here, here is where we have the cutting taking place then it will automatically retract, the retraction that I talked about happens here that is the compliant end effector novelty here.

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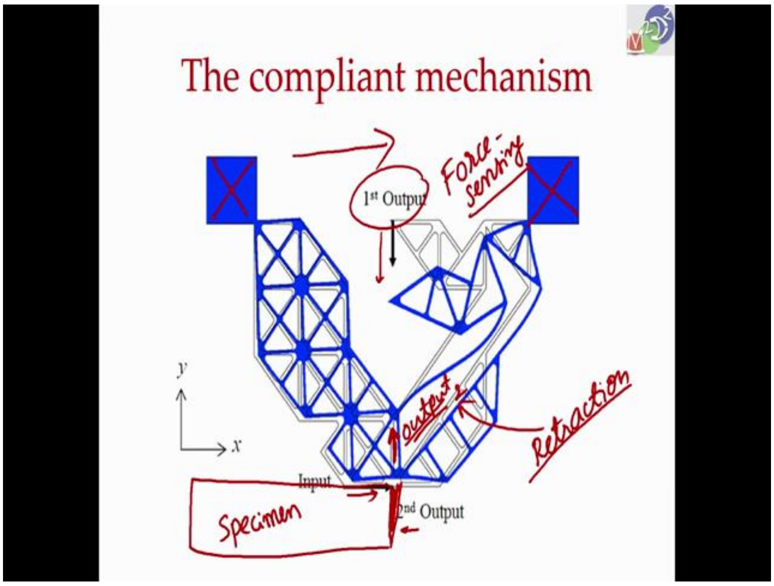

So, here is the thing, when I have input force this input force in this direction because the scalpel will be attached to this; this is the scalpel that you are cutting right that is a scalpel. Now when you move it like this applying force, this point will move in that direction; earlier we had seen that when there is a force in this direction, we see that output is here.

So, we have an input here then what will happened is this point will move up and this point will move down; earlier we had seen that if I apply input force this way this will come down. So, let us look at this in a in a device. So, here is the thing we are talking about.

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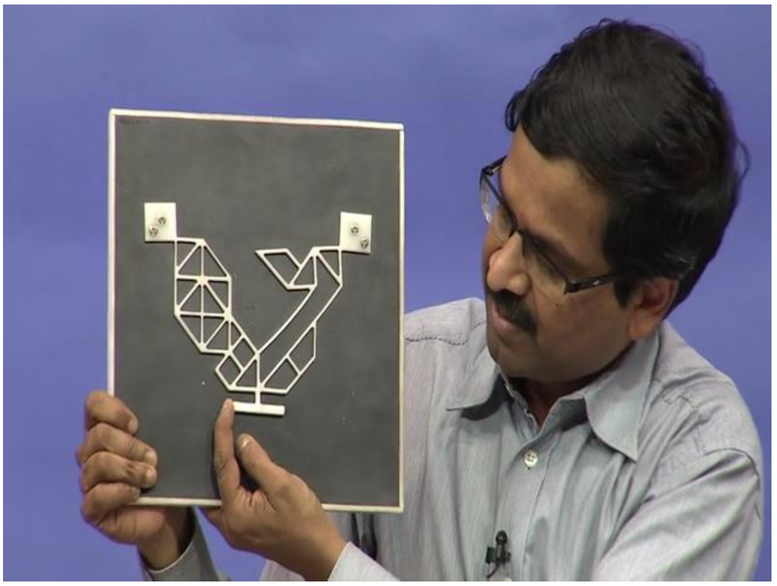

So, let me actually, put it like this. So, now, when there is cutting force, so this way; I apply the force you call see this coming down. So, this point comes down, by how much it comes down we can estimate what the force is here, that is the force sensing principle. At the same time when I do this, this also moves a little bit up that is probably hard to see here, but this point actually when you do this it actually moves up here.

So, what happens is that when cutting force exceeds certain value, this actually retracts automatically. So, that is what is shown in the simulation over here, but when you apply the input force in this direction it is actually moving up. So, this is called a output 2; this is the second output, this is the first output so this is used for force sensing indirectly. So, we sense the displacement and hence is the force, this output 2 helps in retraction. So, when you apply a lot of force here then it would move a lot. Imagine that the whole thing where it is attached to some frame, this whole mechanism is moving let us say like this to cut some tissue here.

So, here is where let us say some tissue is there, you just moving the whole thing it is going to cut, as and when the force in this case when it is cut like this force will be in other direction, so it probably make sense with what we have now indicate here. So, let us say that the scalpel is like this and we have the specimen to be cut over here, a specimen is here when this moves like that cutting force of course, will come like that will make it go up. So, depth of cut will change a little bit depending on the stiffness and when the force exceeds certain value, then this displacement from over the scalpel this output to will be so much that it will not cut any more that is the idea.

So, on the one hand we are able to sense force; in other hand we are able to retract when cutting force exceeds certain value for which we design the mechanism. So, that is what the compliant mechanism is doing here.

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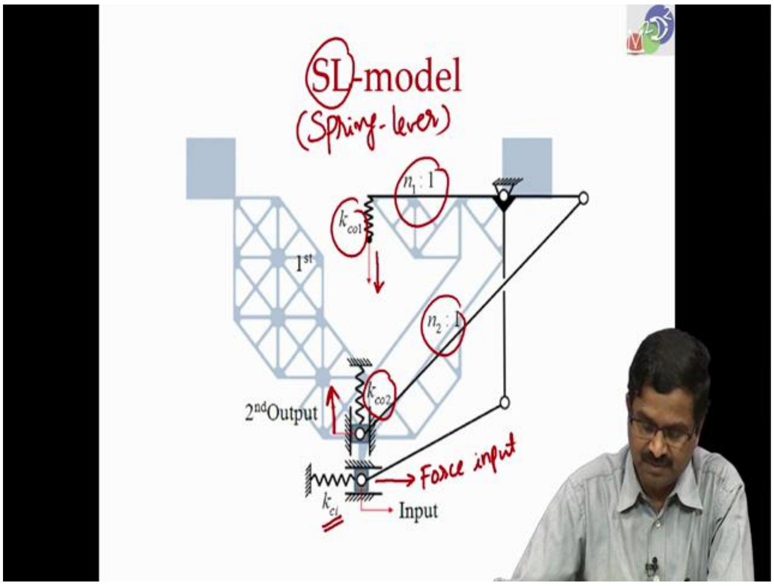

For which to design we had looked at this spring lever model, that we have already discussed; spring lever model SL model. So, if you look at this thing here, the input is here there is some input sides stiffness K ci. So, when there is force like that this is the force input; an input force, then 2 things happen; one is that this point moves like this to indicate the displacement and to indicate the force directly, at the same time this point actually moves up as it is shown.

So, retraction; so there is a knife edge that retracts without cutting. So, we can make this model there are leverage ratios 2 of them now and there are 2 outputs side stiffness; earlier we had taken single input single output spring lever model, where you had K ci, K co and n, but now we have K ci1 input and then K co 1, K co 2 and there is n 1 and n 2 leverage ratios. So, that is how this model was built, so that we can design for a particular cutting force.

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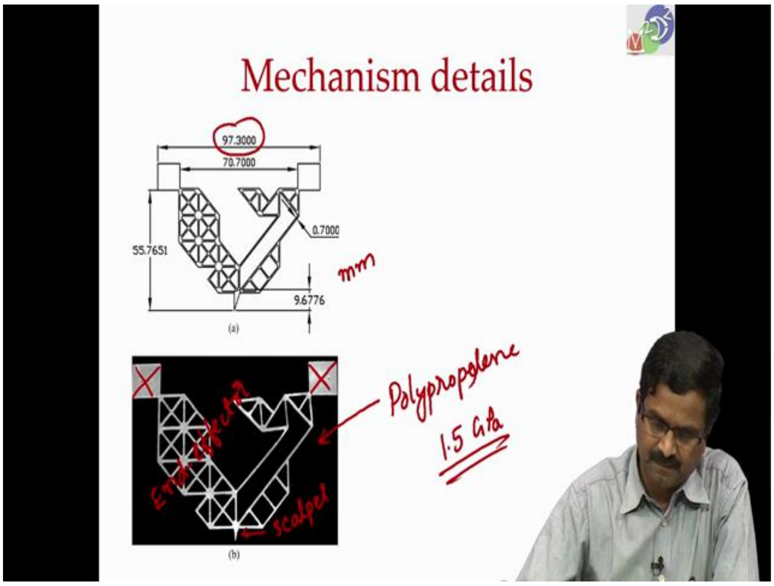

Here are the details of the mechanism called dimensions are in millimeters, so the blade is here, which is shown over there. So, that is the blade attached to the mechanism and these are going to be attached to a carriage and the whole thing will be move to cut. So, this is like now what we called the compliant end effector for the cutting tool.

So, cutting tool is scalpel is here; scalpel is here and this is the end effectors like a robot end effector who have now a compliant mechanism end effector. So, on the dimensions is ninety 7.3 millimeters and so forth, it is a big device made of this materials here is a Polypropylene, this has youngs modulus about 1.5 Giga Pascles, roughly what we had found Polypropylene.

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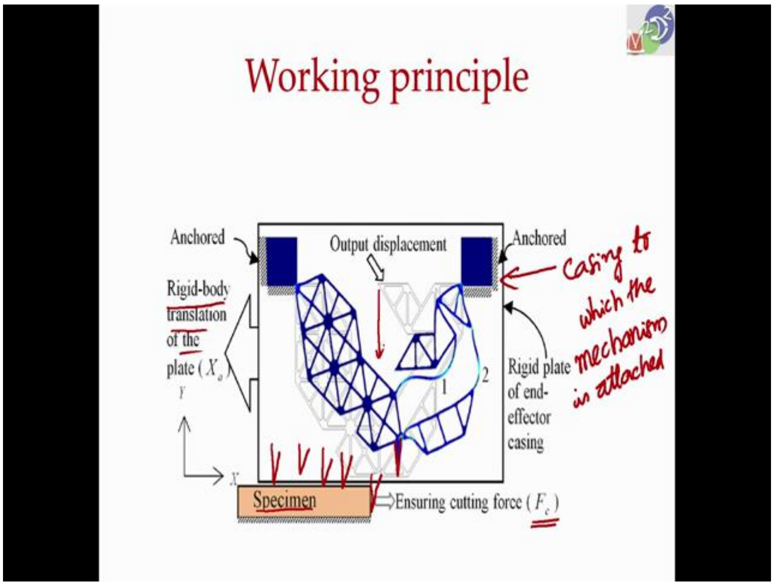

Here is how it works; when you are is the specimen is here and when you are moving it there, cutting force will be in this direction on the mechanism. So, the cutting tool once again is here, what will happen is when the cutting force exceeds at the some points you see how the non lever deformation has taken place, it has moved here it retracted.

So, as you are doing because of force it just goes. So, since if you are still moving this casing, this is the casing to which the mechanism is attached casing to which the mechanism is attached it keeps going, but then this is retracting so what will happen is this scalpel when the cutting force exceeds, will simply ride on top of it or sometimes may even go back. So, it just goes like this without cutting; that means that we are ensuring that cutting force beyond certain value is not even applied on the specimen so that is the thing; rigid body translation on the casing will basically ride over it, that is how it works.

So, there is a cutting force F c threshold put on the mechanism. Once again output displacement here is going indicate how much cutting force is there, this is the working principle of the device.

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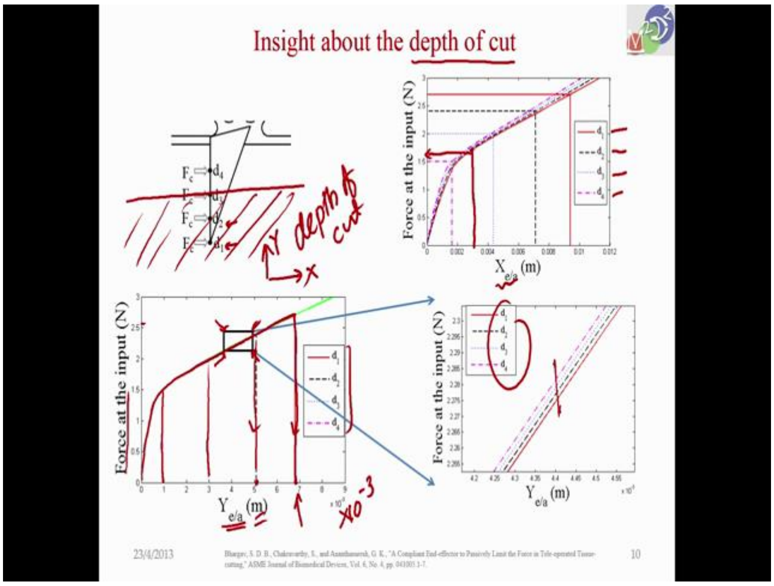

In order to do this we have to pre calculate certain values about the effect of the depth of cut. So, when we have a mechanisms if you take depth of cut at d 1, d 2, d 3, d 4 that is how much of the scalpel is inside the tissue; let say if it is d 3 that means, that the tissue it is up to that d 3; d 4 means up to that d 1 means just dearly touching, d 2 is little bit inside so this indicates the depth of cut. For a force F c applied at different depths of cut, what we have shown here is the force at the input versus the Y displacement. So, y displacement here is in this direction that is Y and this is X.

So, what we have here Y displacement goes like this, it does not depend so much on the depth of cut, because when I zoom in this portion over here into this, then I see that there is difference, but otherwise for all depths of cut the Y displacement is the same whereas, X displacement there is difference. So, the X displacement for depth of cut one the red line and then black dash line, blue dotted line and the magenta dot dash line. So, that slightly different in terms of the X that is how much it moves in this direction, X is this way Y is that way. Y is at retraction that is what interested and that does not depend so much on the depth of cut.

By knowing the X displacement we can see what the cutting force is at any point; so, we do not, but actually we are not measuring displacement here we are measuring at some other point in the mechanism as we explain in the previous slides. So, if we know the displacement let us I have displacement some value here then I would know depending on the depth of cut then I would know what force it is. So, that is how it is going to work in terms of the force a sensing as well as limiting.

Limiting is that you see if you have a depth of cut of d 1, then the curve goes all the way here and then at that point it comes back. There is when it does is that by that time the Y displacement has exceeded some 2.5 input displacement is there, Y displacement is 6 point nearly 7 millimeter, this is meters here you cannot see this says 10 power minus 3. So, meaning that it is in millimeters; nearly about 7 millimeters Y if the force is 2.5 Newtons with the depth of cut d 1, I have already retracted. If it is depth of cut is d 2 about 5 millimeters, because that is when it comes down like this and this is 3 and this is about 1 for d 3 and d 4 depth of cut.

So, based on the depth of cut and the force we see when it retracts. So, this a priori analysis enables us to estimate this without having to go to finite element analysis, which in this case is very non-linear we do not need to do that because we want to do it in real time.

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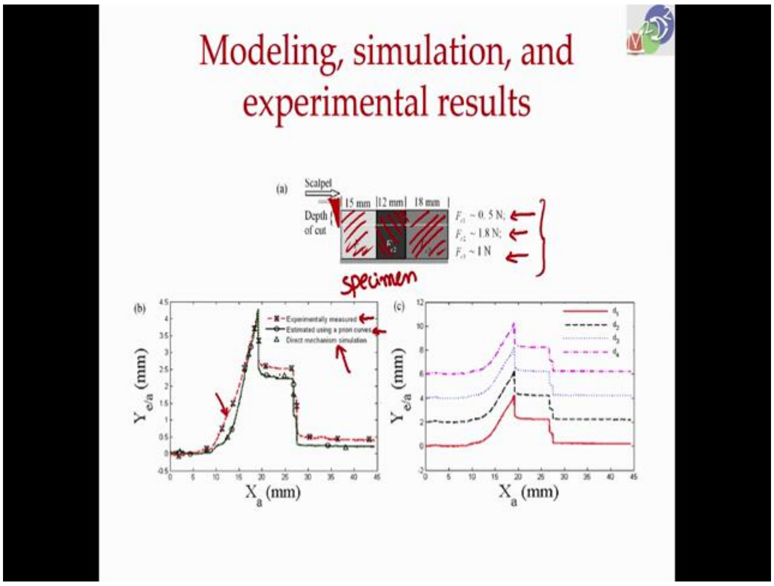

So, based on this model when we have an experiment where there are different cutting forces required for an inhomogeneous specimen. So, here is a specimen that was actually simulated and also made experimentally. So, there is this gray one that requires half a Newton cutting force, and then this black one requires 1.8 Newtons and then this darker gray one requires 1 Newton.

So, as you bring the scalpel which is where it is, as you bring the scalpel and start cutting. So, you can see that it was slowly increasing the force and then it suddenly jumps because it has to go to a hire one and then comes back to over here to cut about 1.8 Newtons, then comes back and cuts the 1 Newton and then goes like the way you are cutting, it just shows how Y and X displacement change for various depths of cut here and we can see for each force how it is doing it. So, here we are showing experimental measurement and then estimated using this a priori curves and then direct simulation that was done later to see how they go; obviously, experiment which is this dash line differ slightly because there are lot of uncertainties in the experiment, but the actual full simulation and estimated using a priori curve they match quite well.

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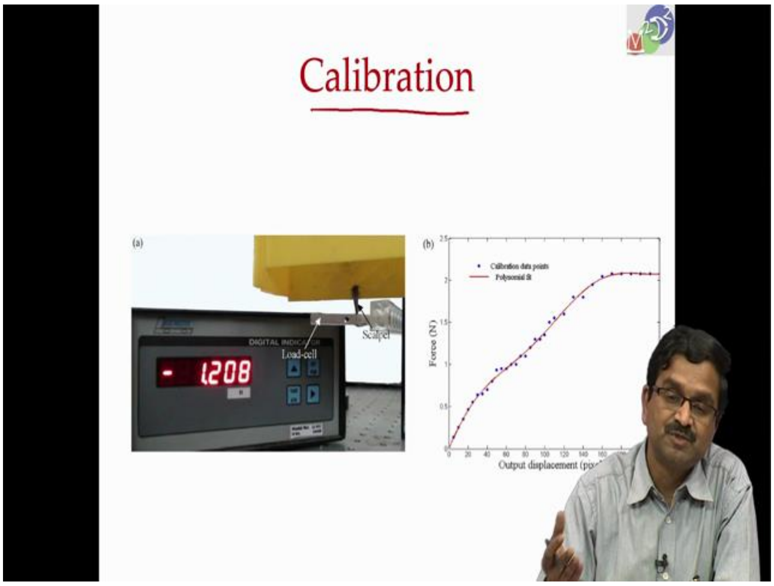

So, we also did calibration using a load cell. So, that when the scalpel is moving how much force is there, so there is a calibration data points for a particular thing that we want to cut, so we will know how it varies. So, we have the calibration done by comparing with a load cell of cutting some specimen, which had a force varying as shown in this case.

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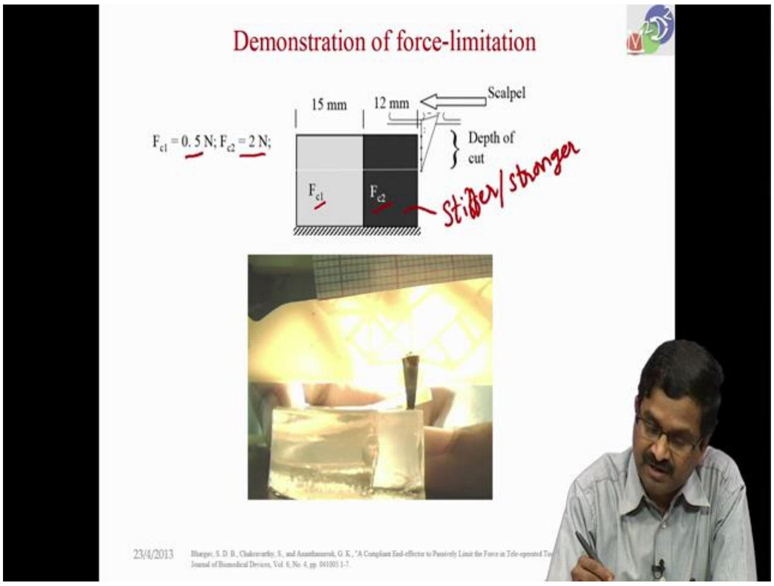

So, we made a specimen that has cutting force equal to 0.5 Newtons and 2 Newtons, F c 1 and then F c 2 so; that means, that this is little stiffer or stronger either way stiffer or stronger, but compared to this light one when we are cutting how it would go at different depths of cut is what we can use the model and verify.

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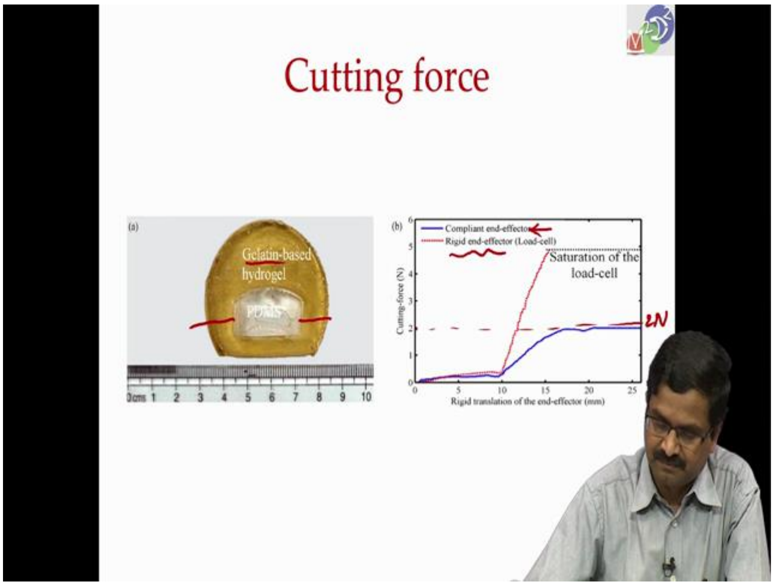

So, here is the thing where we have a Gelatin-based a hydrogel which is very flexible and soft, and then we have PDMS which is also soft, but related to this hydrogel it is stiff. So, when you cut along this. So, you have done in a way that if you cut with a rigid end effector, which is take a scalpel and go you will cut hydrogel and you will also cut PDMS. So, you will cut through the whole thing whereas, if you cut with our compliant end effector that is a blue curve, it would not go beyond this 2 Newtons. We have 2 Newtons the weight is designed so it will cut through the Gelatin and it would not cut to this rest of the portion; it will just cut here and then skip over and then start cutting later, it will be ride over it as you will see in a video.

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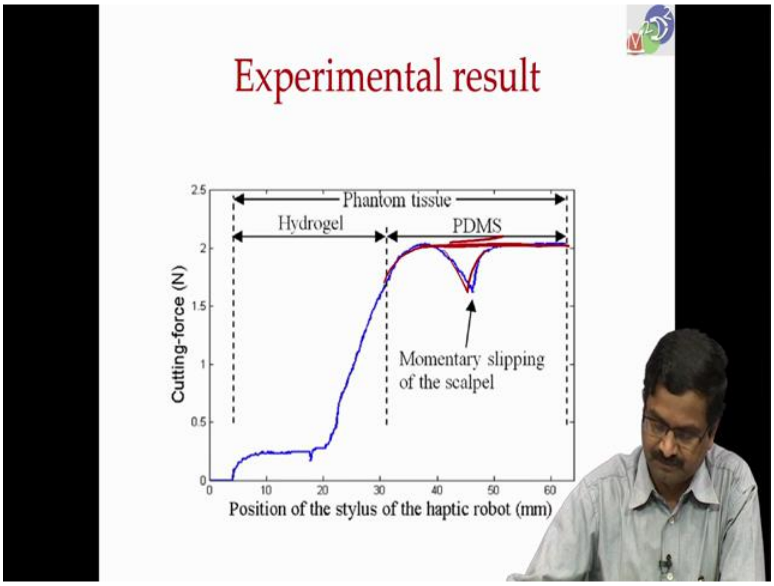

So, here is an experiment the cutting force. So, when you go to the hydrogel it is going to some 2 newton the movement PDMS is encountered, it just stays there 2 Newtons. So, it will just go there it would not be able to cut if PDMS is requires more force, this is a momentary slip that happen in the experiment, but that can be ignored, but the fact is that there is a passively limited upper threshold on the force.

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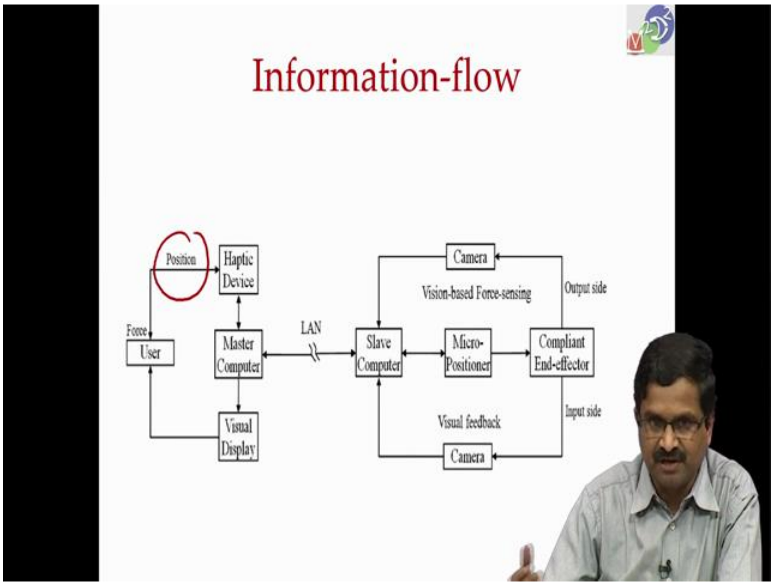

This was the information flow when you Tele-Operation. So, we said at the beginning that you can also do Tele-Operation, now that we have a safe device which cannot exert more force than needed.

So, whenever you have a master slave operation, for a patient is always little bit troublesome to see that a robot or a automatic device is cutting, what if it exerts more force at places where it is not. Now here in end effector, that limits the cutting force so it is more admirable part for this master slave operations or Tele-Operations. So, that you do not have to worry that it is going to exert more force than certain value and the force can be decided based on the design of the compliant mechanism.

So, for that information flow there is user, user's position is related through a haptic device through a master computer and through LAN it is goes to the slave computer and goes to the final compliant end effector. Now the force there come visual feedback and then the competition the force comes to the again master computer through haptic device to the user. So, both ways there is information flow from master this case human and the tool which is a slave; machines are always slave to humans, so that is what we have here the information flow.

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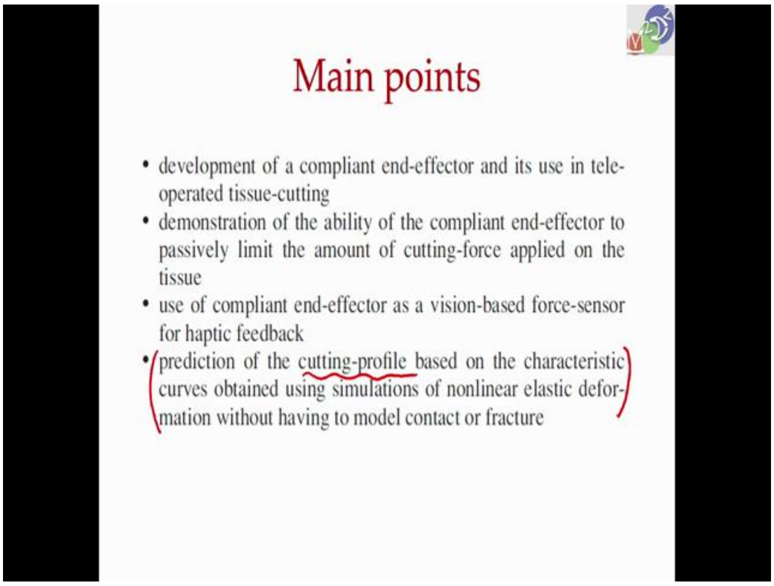

So, to summarize in this particular device, what we have done is the developed a compliant end effector, whose 2 features of sensing forces and limiting the cutting force are demonstrated. So, it demonstrated that passively limited the cutting force. So, here we have less strong or weak material can be cut easily, when the strong material comes it will just retract. So, let us look at the video and come back to this here.

So, let us look at this video.

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So, you can say the compliant mechanism we can see scalpel and move this stylus master, the slave would be the cutting tool actually cutting. So, we can see how the cutting tool is moving where it will lift off when the thing come, so let us watch this and I will be another showing another movie where it will actually lift off.

This is the master and then the slave we saw the other end.

These are the 4 touch screen (Refer Time: 26:58). So, it was screened and you move it and that will go to the slave.

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So, let us look at this lift off operation, this is the hydro, this is the stiff PDMS it is rides over it, when it come to the hydrogel portion it will just cut it. So, now, the scalpel is up there not actually cutting, it is just ride in over it and then when it comes to the flexible part it will just depend. Yes, so it went to that and started cutting along this profile. So, the stiff one or strong one it is not cut, flexible one is happily cut. So, this compliant mechanism the retraction feature is used in this particular device.

So, let us look at the main points that the compliant end effector is useful because it has built in safety feature and we also have developed a priori analysis more details you can look at in the paper, where this prediction of the cutting profile also because of this x and y displacements of the input point, that we pre-calculated using finite element analysis and feed the curves at different depths of cut that not only tells us how to estimate the force, but also estimate the cutting profile once you know the stiffness of the work piece.

So, a compliant mechanism can be used in applications where rigid ones will not be suitable, then you would need a sensor or a controller where as this one can automatically go, which is what people find in many biological organisms whether it is walking or flying, compliance is used effectively to passively change things. So, when an insect is flopping wings, people say that insects is actually is not doing this figurate motion on the tip to twist; it is actually going like this, but the compliant unit is actually giving it the slight twist that it needs, similarly walking when obstacle is encountered if you have a robot then you have to have a controller to avoid the obstacle and go; whereas, if there is compliance it will simply move away from the obstacle by bending or deforming and then moving on.

So, we had shown one video of a robot with compliant legs several lectures ago, that is where the compliant design actually helps. If you use compliant design effectively you can reduce reliance on control, you can avoid having to control something which natures seems to do extensively.

Thank you.