Mechanics of Human Movement
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Lecture – 49
Design Considerations: Prosthetic Knee

So, we are looking at Prosthetic Knee Design and quick to quickly recap stability in the stance is important and the swing control is also important. Swing control may be at a single speed or if possible adapting to multiple speeds of walking would be desirable. So that, a person can change their gait and have the prosthetic knee keep up with their walking with whatever speed they are walking in. And in some cases shock absorption may also be incorporated in the knee. One level of shock absorption that is very important is when the swinging leg moves forward ok.

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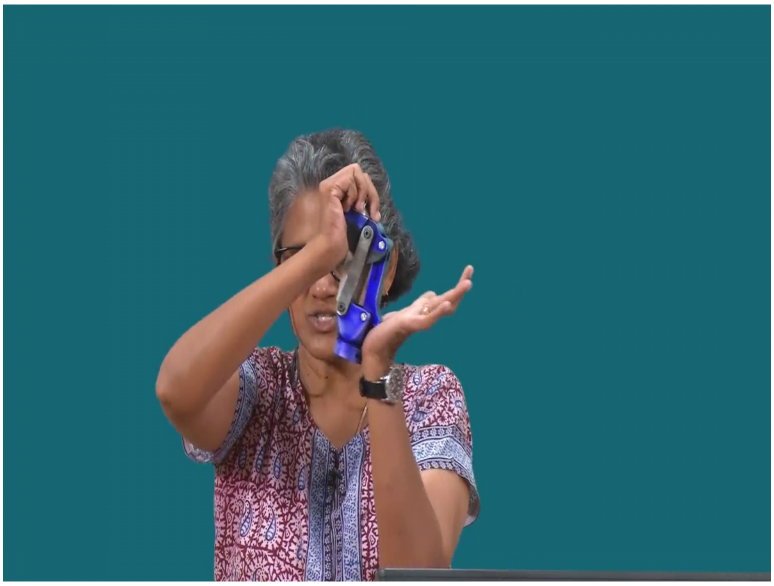

So, in all these knees you will have an extension stop ok. So, in a mechanical knee, so the knee cannot move this way ok. The knee can only bend this way. So, you will have what's known as an extension stop, that prevents that keeps the knee in full extension and not let it hyper extend ok. So, when the swinging leg contacts that stop, you need some dampening there. So, that it is not an impact it is not hard impact at that point.

So, you need some shock absorption. Other knees also some knees may also incorporate shock absorption to in the form of some limited stance flexion ok, like the knee does in the when we walk. So, that mechanism may also be incorporated in a prosthetic knee. So, the stability in the stance phase as we talked about can be achieved by different means, you can have a actual mechanical braking mechanisms, which when there is weight on the knee lock the knee prevent it from flexing further or today we will talk about geometric stability, where geometry of the knee decides the stability characteristics of the knee.

And then of course, you have microprocessor control knees which use some sophisticated control mechanisms usually with some kind of a hydraulic unit to control the knee movement and to make sure that it breaks at appropriate places ok.

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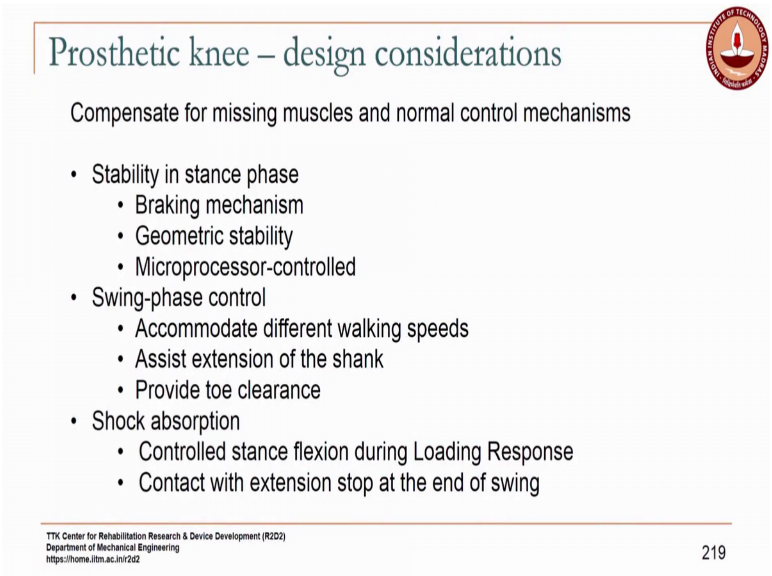

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So, we talked about the extension assist, we talked about this is the knee on the left the geoflex knee. This is the simpler version of it. So, this version that is shown here has this stance flexion feature. Users are not very comfortable with that stands flexion, they it gives them a feeling of instability sometimes because, if they are not used to that.

You know if it is a new prosthesis user they can be trained and they may actually benefit from having that, but an experienced prosthesis user because, a lot of knees do not have this stance flexion feature. So, suddenly when they are. So, they tend to keep their knee well extended in during weight bearing. So, if they feel the slight movement in the need they have this feeling of instability.

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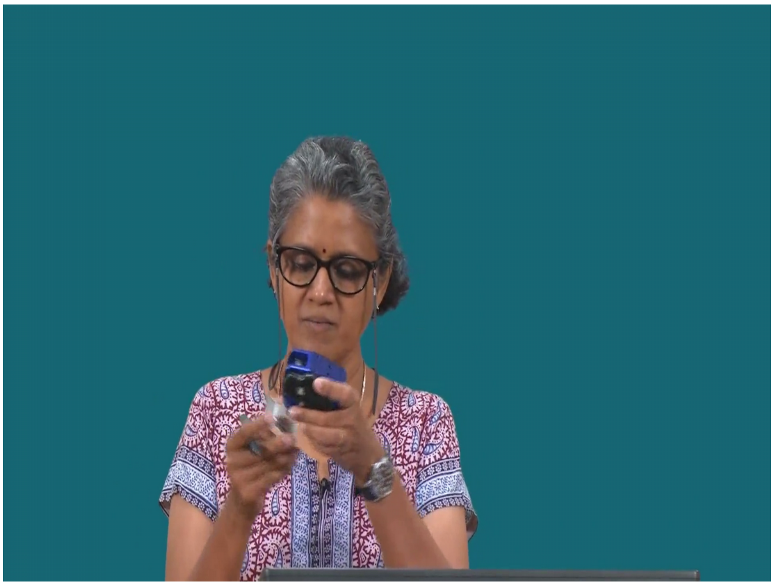

So, not so for them there is a different version of that same knee which is without the stance flexion. So, this is an example of we will talk about polycentric knees in, but you can have a wide range of knees. You have you know what are known as single axis knees. So, if you can classify knees, you see that you can have single axis knees; you can also have polycentric knees.

So, a simple hinge a single axis knee is essentially just a simple hinge ok. It allows that single degree of freedom flexion and extension. And so it is basically just a nut and bolt, you know just a revolute joint that is between the thigh portion and the shank of the prosthesis, I need the prosthesis. So, you have just a simple hinge and then you could have what are known as polycentric knees. Now these are knees that have a moving center of rotation.

So, what this means is like, so between you have the socket, you have the socket and you have the shank.

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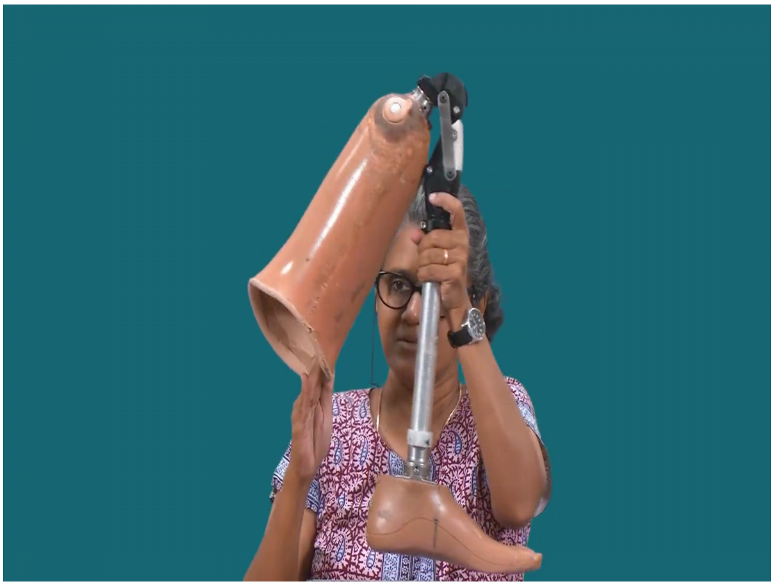

Between these 2, you could have just a simple hinge joint. So, the socket or the thigh rotates about the shank, about that single joint. A polycentric knee is one where the center of rotation of this thigh portion with respect to the shank keeps changing. It is not a single point and we will see what are the advantages of that.

Now your actual human knee itself is not a simple hinge joint ok, if you look at the human knee right, you will see that as this moves the knee center the point about which the thigh is rotating about the shank is actually changing. You have it forms a small semicircular arc ok.

It is not a constant point that is why you have both sliding and rotation, you do not have only pure rotation at the knee. If you had only pure rotation then it would be a single joint, the single axis joint but actually here the instance and instantaneous center of rotation changes ok.

So, they can do some experimental studies to find out what that and this actually looks more like a this kind of a small this is the locus of the knee center in the human knee, but in your usually that the range of motion of that instant center is very small.

So, it can be approximated especially for a prosthesis because, there is nothing here. In the case of an orthosis approximation can cause some problems because, your actual knee which is in the support of braces is moving with this kind of a knee center. And now if you force the braces to move about a single axis that causes relative motion between the device and the person, the persons limp.

And that can sometimes lead to discomfort, that is called pistoning, that is called a pistoning effect, but in the case of a prosthesis because it is nothing there, you can approximate this to a simple hinge joint a single axis hinge ok. So, in many cases the simplest type of knee is your single axis knee ok.

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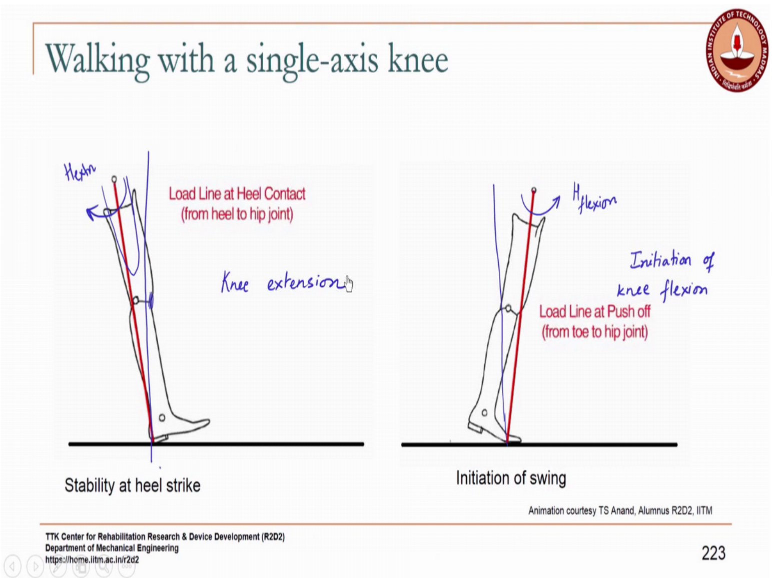

So, now let us see what? We saw that in some cases a lock knee is the solution that is used, but as we saw the lock knee is all not always a good solution for walking because, it causes that circumduction kind of gait or some other compensation that the person will adopt and which can lead to increased energy consumption and also unnatural loading on the other joints leading to degeneration ok.

So, let me just try to explain it with this. This act the video will actually show it nicely. When the person using an above knee prosthesis, say with the single access joint you have a single access joint here at heel contact. At heel contact the load line say is like this ok. Now what is the tendency of the knee, what kind of a moment will it cause about the knee?

This is going to cause a flexion moment about the knee. So, if the person does not apply any moment here at the hip. Then the tendency of the knee is going to be to buckle ok.

So, now, what the person the person has control on the prosthesis only through the residual limb, that is there right that is housed in the socket.

Now, what the person does is, the person applies a hip extension moment ok. So, the person applies a hip extension moment at the time and what that does is, this moves against the there is an extension stop right. So, it will tend to knock the knee against the extension stop.

And essentially what that will do is now the person is pushing back on the ground with their heel. When you do that when I extend my hip and lock the knee, I am pushing back against the ground and that creates a forward force which changes the direction of this ground reaction force, this will move in front of the knee joint because, I have this original thing plus a forward force which changes the direction of the ground reaction force now.

So, that it moves in front of the knee joint. So, when the load line, you know the load line is this line through which the ground reaction force acts, when that is in front of the knee you have an extension moment about the knee which keeps the knee stable ok. So, by applying this hip moment, if the person was not able to apply that hip moment, then this is a problem, but they may have some residual hip strength and they can apply that hip moment and cause this load line to move in front of the knee.

Now, at two off to initiate swing, you need the opposite. At that time if you look at the load line the load line is actually in front of the knee ok, which means that the knee is locked, but what do you want to do? When you want to go into swing you want to unlock the knee. So, in this case, the person applies a hip flexion moment. Here this was a hip extension moment.

Now the person applies a hip flexion moment and that moves the ground reaction force behind the knee joint which will initiate flexion because, now the loading is off you know it is the loading is lower on the leg. So, they want to initiate flexion, so they move they the exert of hip flexion moment which causes the load line to move behind the knee joint, this hip flexion moment will cause the load line to move behind the knee joint and initiate flexion. So, this is initiation of flexion knee flexion, here you want to perform knee extension.

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Mechanical lock is only to prevent hyperextension ok. So, the knee extension from you know to prevent it from buckling, that has to be controlled by the hip. So, we do this when we walk to some extent, we are also we apply this extension and flexion moment of course, we have control over the knee. The knee flexion is controlled. So we do not have; but a person with an amputation necessarily has to apply a hip extension moment at heel contact and then, in hip flexion moment at toe off in order to initiate knee flexion to initiate swing.

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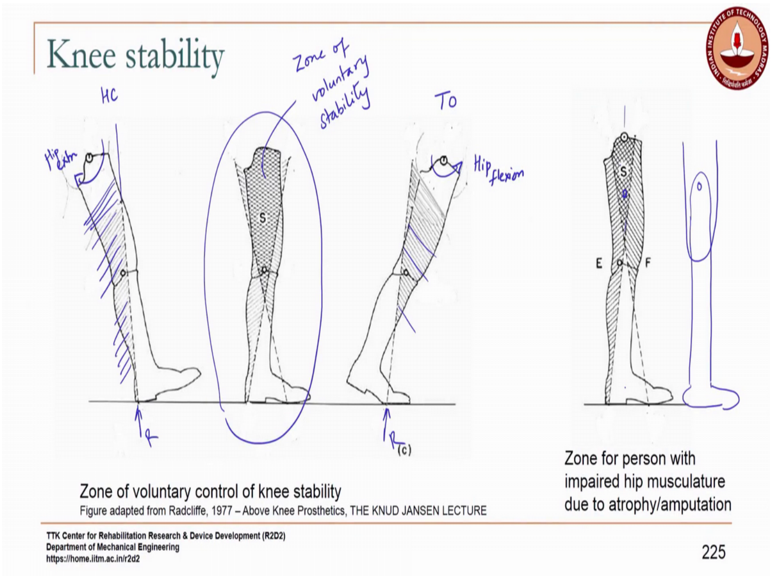

So, what this does is if. So, we know that, if with the application of this hip moment if they are able to move the load line to this place. Then, as long as the knee is located behind this line, that is my stable region right. As long as the knee joint is located, if I am using a single access knee as long as the knee is located behind that load line, that is my zone of stability. Now if I look at so, this is that heel contact at toe off by applying the hip flexion moment. So, this is by applying the hip extension moment ok, hip extension moment and here I apply.

So, when I apply the hip flexion moment and I move the load line say if this is the reaction force, I move the load line behind the knee. As long as the knee is in front of anywhere in this region in front of this I can initiate flexion ok. So, this if I superimpose these 2 on this, this diagram is those two superimposed.

So, then I get what is known as this zone of voluntary stability. So, what that means is so that is the region that overlaps. If the knee is located in that region, in this cross hatched region where the 2 meet, in that common region if the knee is located then, with my hip moment voluntarily I can control stability at heel strike and initiation of flexion initiation of swing I have the ability to control them.

Now, what happens is so this is with if I am able to apply normal levels of hip extension and hip flexion moments. Now for a person who has impaired mus hip musculature, it could be because of atrophy, it was you know because of amputation, because of whatever reason. This zone because, they are not able to move it when you superimpose the zones because, the amount of moments they would be able to apply our lower than an able bodied person this zone shrinks ok. So, you can see here that this zone is smaller than the zone in a person who has normal hip strength ok.

So, now what happens if you locate your single access joint? So, in many cases if there is a single access joint what they will do is they will actually locate it slightly, posterior from the hip anchor line for instance ok, this is your hip anchor line. The alignment of the knee will be such that its located posterior could be 10 to 15 millimeter posterior to that line. Why would they do that? Because at heel contact, you are ensuring that even with minimal hip strength the knee will remain behind the load line ok.

So, you are actually offsetting it from where the normal knee would be to ensure stability at heel contact, but what does that do to initiation of swing. Now the knee is hyper stable at toe off right its further behind where it should normally be. So, you can see here even though this knee location is in the area where it would provide stability, for initiation of swing it does not lie this is the common region ok. This knee is stable; it is still in the stable region in this crosshatch region it is locate. So, it will provide stability and heel strike, but initiation of flexion becomes very difficult.

So, at swing they will have to really you know complete unload the knee before they can flex the knee. Again that leads to an unnatural gate. So, they cannot because, the knee will stay locked as long as there is any load on the knee it will be very difficult to flex the knee because, the knee the knee center is now even more posterior than the normal case. So, a single axis knee obviously. So, now, the other option is if I cannot have a single axis knee, here and if this is the zone that I have then perhaps I should locate my knee somewhere here.

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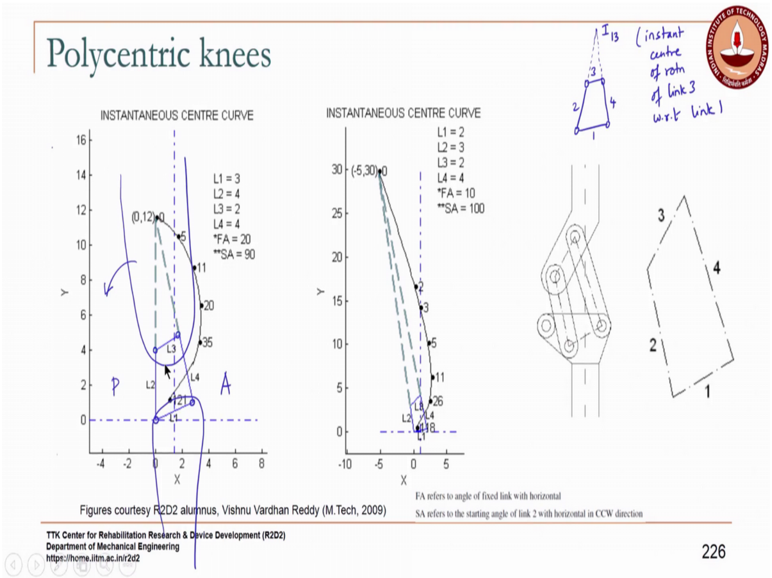

It is a possibility. If I locate my knee there, then with whatever muscle control I have I can control the knee. So, my socket would still be like this. This would be my knee and my shank would be like this. What's the problem with this?

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When you sit down, when you sit down your thigh is going to project. You cannot sit normally with a single access knee in this kind of a location. So, now, what do we do? This is how the evolution of a polycentric knee happened ok. So, if you look at this zone, you want the knee to be located there, but you also want the need to move to somewhere down here when the person is sitting when the knee is flexed ninety degrees. So, that it appears normal.

So, really what you want is a moving knee center, you know at full extension when the knee is fully extended rather, high location of the knee is desirable so that, the person the prosthesis user can control the prosthesis better by applying their hip moments.

But location of a single axis knee there is cosmetically unacceptable. So, that is how the polycentric or the linkage type knee evolved ok, so in a linkage type knee instead of a single axis ok.

Say you have the simplest type is a 4 bar linkage ok. So, I have these 4 links L1, L2, L3 and L4. L3 is what is attached to the socket. L1 is attached to the shank ok. So, you have 2 links, you have this linkage instead of directly connecting the socket and the shank with a single access knee, you have these two additional links in between and what does that do?

Now, what happens is, if you remember your K dot kinematics and dynamics, you saw that if you have 4 links like this ok, then say this is 1 2 3 4. at any instant 3 is rotating about 1 ok, 1 is the fixed link say ok. So, with respect to 1, 3 is rotating. 3 is motion can be described as a pure rotation about the instant center I13. And how do you find instant center I13? You extend link 2 and link 4 and where they meet that is your instantaneous center of rotation of link 3 with respect to link 1.

Now, in this case what is my link 3, my link 3 is my socket and type. What is my link 1? My link 1 is my shank. So what does I13 become it is essentially my knee center. So, that is my virtual knee center at that particular instant.

And now what so with this 4 bar with this kind of a linkage as link 3 moves, as it flexes right as the socket flexes with respect to the shank, what happens to this instant center it does not say its stay the same, it keeps changing because, every time those two links the intersection of those two links gives you the instant center. Then what happens is if you plot. So, at 0 degrees of flexion that is if the angle of link 3 the socket with respect to the shank is 0 then, this is the location of the instant center.

So, I can locate it fairly high and also maybe behind the load line at full. Then as the knee flexes you can see that it rapidly moves down, these points these indicate the degrees of flexion. This is just some random geometry of the linkage, but you can see that it moves down and so say at 120, it comes very close to where the anatomical. So, beyond 90 it is when it crosses you know, 70 something like that then it is always in that region near the anatomical knee center.

So, what that does is, so here for instance, you have this link, so you have the fourth pivots here ok. So, this is link 1 your shank, this part is rigidly attached to the shank. So, it forms part of the shank, this is your link 1. Say let us call this link 2, link 3 is rigidly attached to the socket and this is link 4 ok, it is a planar mechanism.

So, now, if I flex the in instant center at this point is the intersection of these 2, it is somewhere located somewhere here ok. So, I can flex with minimal effort and then as I go as I bend you can see that now the instant center is at the intersection of these 2 links, it is somewhere here, which is close to the so, for sitting it looks fairly normal right.

You do not have the cosmetic appearance is very much acceptable. So, this is and this kind of a knee therefore, provides the mechanical advantage. So, for a person with reduced hip effort, they are now able to control the knee better to control the stability as well as the flexion of the knee.

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Now of course, as the geometry changes, so different four bars will have different characteristic instant center curves. It is not going to be the same for every 4 bar because it really depends on where these 4 pivots are located.

So, this is an example of geometric stability. There is no breaking mechanism in this which is providing the stability. The stability arises because of the geometry of the mechanism and by you know designing it with appropriate geometry, you can ensure the stability of the knee for the user, depending on their residual strength. So, this is an example of a polycentric knee ok. So, here again you see it is a 4 bar with a different geometry and that is the advantage.

So, even though it does not look like a normal knee, that it does not look anything like a normal knee and it does not even follow the pattern, the motion of the normal knee, but here what you are doing is you are providing some compensation, you are providing a mechanical advantage to the person using the knee because, they have some impaired musculature, because they do not have the same muscle strength, you are compensating for that.

So, here is an example where you are not just mimicking not you are not even mimicking the motion of the knee, but you are actually providing some kind of an advantage to the user to compensate for their impairment. So, this is the reason why something need not always be biomimetic, just as you saw with the prosthetic foot. It need not look like the foot it need not even function just like the foot. As long as functionally it accomplishes the same goals ok.

So, here functionally for walking the goal or even for standing the goal is to ensure stability with minimal effort ok. And then for smooth walking you also need to be able to swing for swing the leg forward. So, this provides both of that both of those functionalities without looking like the normal knee and without having all the other contraptions of the that are needed to control a normal looking.

So, if I designed something that looks like the normal knee control of that become could become much more complex. You saw even with the single axis knee while it is a very simple design. So, this is one level of complexity, this is a higher level of complexity in the design.

So, you know, but a 4 bar is still relatively easier to maintain. Some of these former still may have only frictional swing control, but they still function you know and significantly better than a single axis knee, they can provide better functionality. Especially if you are on uneven terrain and things like that stability is very important, how much you can voluntarily control the stability is a key aspect of the knee. So, you can see here there are various geometries of these 4.

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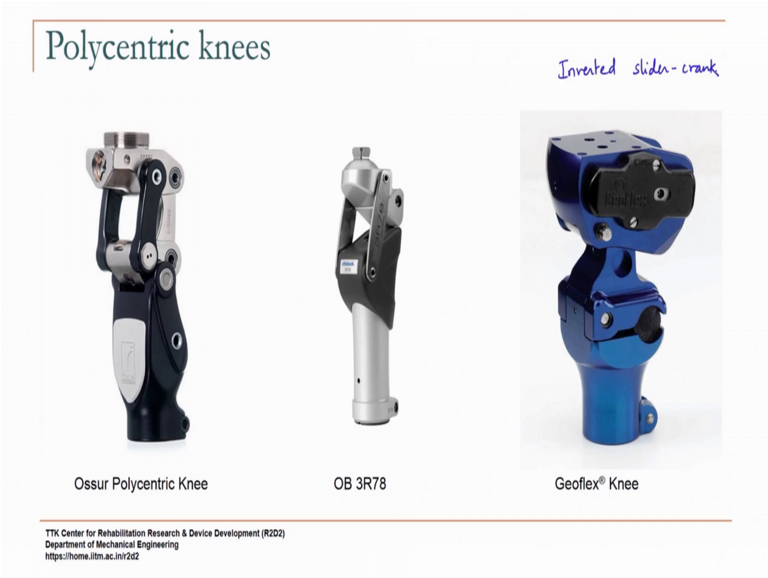

This one is actually a 6 bar needs a more complex mechanism. And this knee actually instead of using a typical 4 bar.

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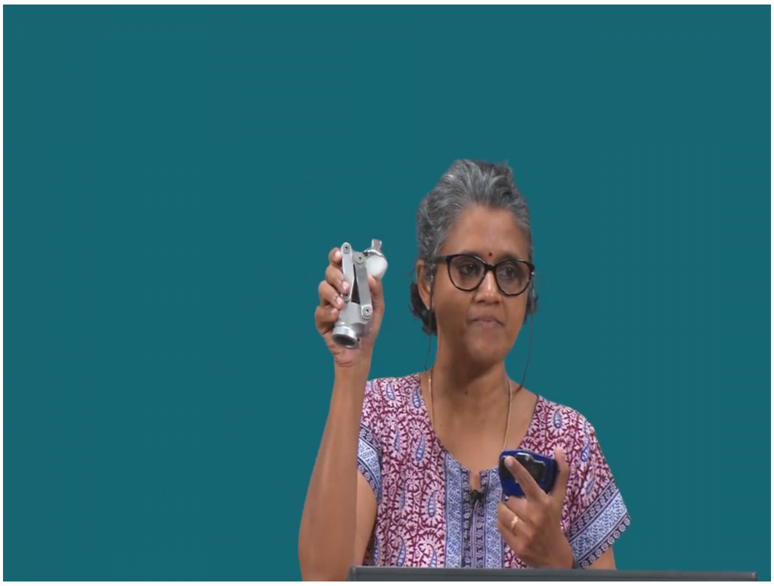

So you will see most of the knees are these kinds of 4 bars ok, where when I say 4, but one is the shank one is the thigh and then you have two links. And we treat it as a 4 even though, you have 2 and 2 of each, if you look at it from a kinematic perspective it is just a planar four bar mechanism. It has more links, but that is first stability in the it is for structural stability in the other planes. You know in the frontal plane as well as the transverse plane, you cannot have just a planar mechanism because, that will not be able to sustain the loads and the other planes.

So, so you basically you basically duplicate that linkage on the other side to achieve that, but kinematically it is just a 4 bar, this, this, this and this 4 legs is what. So, different geometries are there and always if you look at the linkage it only the pivots are what matter. The shapes of the links do not really they are shapes of the links are for other reasons to ensure that it clears properly and you know it to ensure that you get sufficient flexion of the socket and things like that, but they are not really the pivots are what determine the geometry of the knee.

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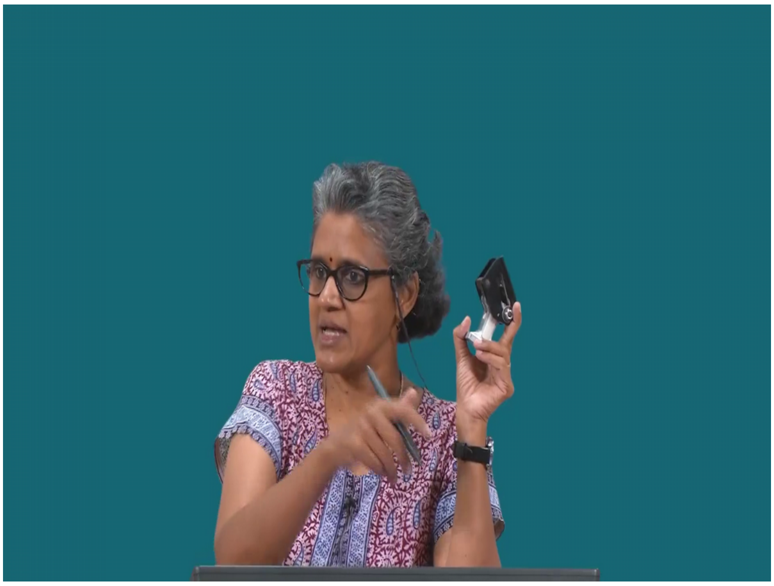

This knee here and this is what it looks like on the inside this is to show you that. This knee is not a 4 bar, but this is also a polycentric knee and this is actually an inverted slider crank mechanism.

So, instead of so it achieves the same. So, you still get that kind of in fact, this is a very stable knee because, if you look at the instant center curve the knee center remains behind the load line, in the in the case of this kind of a regular four bar So, if this is the anterior direction, this would be the anterior this would be the posterior direction ok.

This is my AP direction. So, as this bends ok, this knee center moves rapidly down and forward. In the case of this mechanism ok, so if this would be the anterior direction as this bends ok, this it has a curve such that the instant center moves like this. It stays behind the load line for a greater range of flexion, this type of a design ok.

And the advantage is that it provides so even if the person lands on a slightly flexed knee they can quickly recover because, the it tends to be inherently more stable. This has some other disadvantages so, but stability wise, so especially for elderly people this kind of a knee is very useful, it is very it provides them that additional stability. It has a slightly different; it is so it uses an inverted slider crank instead of a regular 4 bar.

An inverted slider crank is also a version of a 4 bar because, a slider crank is nothing, but a 4 bar with one pivot at infinity. And an inversion of that is again you know belongs to the family of 4 bar, so it is this. So you will see that there are knees with very different geometries.

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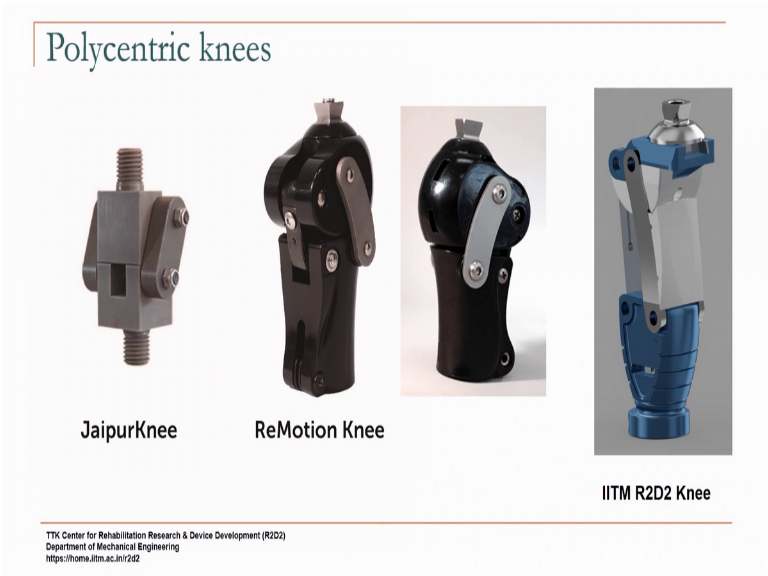

These are a couple of knees that recently are have been they say they have designed it for developing countries. And mainly what they have tried to do is minimize the cost. So, they are using plastics, they are using you know molded injection, molded plastics and things like that too because, obviously this kind of knee would be more expensive than your simple nut and bolt, your simple nie bolt right.

So, these, but since a 4 bar has since a polycentric knee has advantages, they have tried to come up with these designs for developing countries. Unfortunately they have not really looked at the functional aspects so much, they have focused predominantly on the cost reduction, but they are pretty much used, they have not really paid much attention to the geometry of the knee and whether that is suitable for the developing countries.

And that is one of the thing we did one of the things we did when we looked at all the existing geometries and then decided to design our own knee here. The other advantage I will just quickly show you a video

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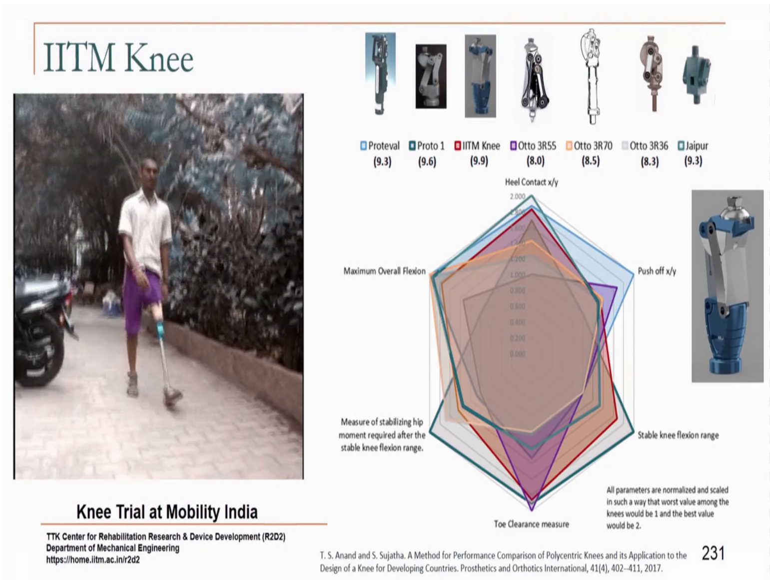

So, if you look at so, we looked at all these different knees, some of them are many of them are commercially available. And then we looked at this was the first prototype that we built proto 1.

And then, so we looked at various parameters, we identified various parameters related to what affects stability in a polycentric knee ok. So, one is you know what you call the effort at heel contact, then the effort is push off. Do not worry about what this x and y, those of you who are interested can read this paper, but x by y is sort of a ratio that denotes that shows what this, a heel contact effort will be the muscular effort required.

Then something called the stable knee flexion range. So, up to what amount of knee flexion, so even if the person lands because, that is very likely if you are walking on uneven terrain. It is likely that every time you complete swing your knee may not be fully flexed.

And you will land; you may contact the ground before you are fully extended, before the knee is fully extended. So, up to what flexion can that happen and you will still be stable; so, different things like that and maximum overall flexion. You know as I told you since we do not in developing countries we do not always sit in chairs for social things we may need to or they may be in more cramped spaces, like you know even in the classroom here, you do not have a lot of legroom. So, you may not be able to sit, you may have to actually flex your knee more to sit comfortably or in a small car or in an auto places like that.

So, the numb amount of knee flexion that is required maximum knee flexion that is possible, the requirement is greater. So, you can see here that you can have a lot of knee flexion. So, it is in many cases it is limited of course, by the socket, when the socket contacts the knee that is when you are knee flexion stops; that is when you get your maximum knee flexion. But what happens is in many cases in the commercial knees, they will only report we found that they report things like they report high values of knee flexion, but if you actually put a socket on it.

So, now, with without the socket I can get this much knee flexion right this is not a commercial name, but still I can get this much knee flexion right, but if I put a socket like that on to this then I might only get about 90 degrees. That is what happened with our first prototype ok. When we looked at it, I mean it is the mechanism itself; if you look at it you get this much, but practically we were not able to get more than 90 degrees. And the same thing with other knees, so in the market many of them will report knee flexion like this, they will say 100 and 60 degrees of knee flexion, but whether it is practically achievable is a different story.

So, when we did our optimization we took a socket, we took like a spherical socket and then compared the knees. If all of them were fitted with the same socket then what would be the maximum knee flexion that you would get, taking in taking into account constraints like this So, we did an optimization of all these using all these different parameters and constraints and the red one, the goal was so, if you look at this radar diagram whichever knee has the best score.

So, we compared the scores on all these 6 counts. This is just one method of comparison you know and there is no weightage or anything a specific weightage here assuming everything had equal weight, we said ok.

The best knee gets a score of 2 ok, the worst knee gets a score of 1 ok. So, in this diagram we just graded it like that. And so the objective is to get as much area as possible, you want to reach out to all 6 corners. You want to be the best on all these parameters which are which we identified as something for walking on uneven terrain.

And then we came up with this red one, the red knee is this R2D2 it. That is the knee which provide that is the geometry which provided this the maximum score on all these counts. Now you can have other editions, so they you know in the next level we may actually add some more parameters like we have now studied the swing behavior some more in our research and we found that maybe we can add 1 or 2 parameters to the optimization to get even better performance.

Of course, you can keep improving or you can say at some point I have something that is fairly good and the goal is now to get it to the market, which is what we are working on now because, you can keep improving something, but at some point you if you want it to actually benefit someone you are going to have to say ok.

Now I will stop here and take it forward. If it is just an academic exercise you can keep optimizing, you can keep coming up with 10 more parameters, you can keep doing that, but practically you have to stop somewhere. So, if you look the other advantage of polycentric knees the other big advantage of polycentric knees is that as because of the linkage configuration, as the knee bends the distance this shank is actually shortening ok.

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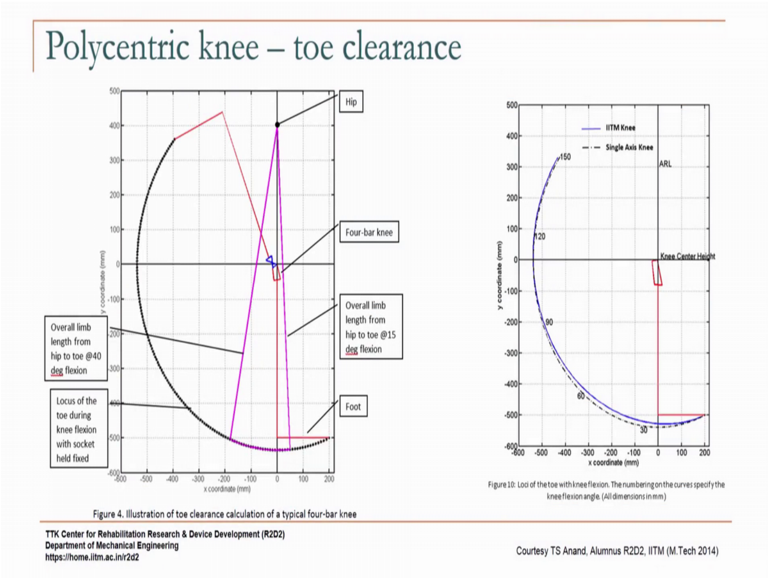

So, because of the linkage configuration if you look at, if you plot it is called the shank shortening effect of a polycentric knee and what happens is if you measure the distance the overall limb length from the hip to the toe ok. So, from the hip to the toe, so here and if you plot that the knee flexes. You will find that it is shorter than in the case of a single axis knee.

So, if you use a single axis knee, so what that tells you is you can get greater toe clearance with a polycentric knee. So, this is a known advantage, this is another known advantage of a polycentric knee that you can get greater toe clearance, which again facilitates better walking on uneven terrain. So, you can get anywhere for you know 20 to 40 millimeters more than a single axis knee. Again it will depend on the geometry of the knee.

So, you can see here a single axis knee the black one versus the blue one. So, with different degrees of flexion you see that this you get better toe clearance ok. And that was the other parameter we used for comparison that was one other parameter we used for comparison among all these different knees ok, which one gives the best toe clearance, how do you maximize the toe clearance. So, now, the reason you are not able to hit all 6’s many of them are competing measures ok, many of them are competing quantity, so you increase you gain on something, you are going to lose on something else.

And that is why if you see the red one, it does not hit the maximum on any of any individual parameter. There are some of these others hit the maximum, so even the first prototype. For instance the stabilizing may hit moment or something it was the best, but its problem was maximum overall flexion was very limited. So, there it got a one or yeah it was the lowest of the lot in that one. So, you can see that since these are competing measures, some other knee may have had like this blue knee had a very good maximum overall many of them had high knee flexion maximum overall knee flexion.

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This one also had this knee here which I also have this is the this is actually a 4 bar knee which also has a pneumatic unit here. So, it is actually a 6 bar you consider the pneumatic unit the piston and cylinders. So, this is a knee that is 6 bar knee. So, you can see here there is there is a 5th link and then a piston that goes into a cylinder, cylinder which is housed in this shank.

So, this is a 6 bar knee, but functionally as far as the instance center is concerned it is basically a 4 bar. So, it would function even without those extra 2 links, the extra 2 links are for the swing flexion to control the swing flexion and extension, not the they do not influence the geometric stability of this knee. To find the knee center you would still use only this for bad portion of the ok. So, a polycentric knee can provide more functionality than a single axis knee ok. Tomorrow we will talk about this the more sophisticated microprocessor control knee and then I will tell you about a few other assistive devices to wrap up the course ok.