Mechanics of Human Movement
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Lecture – 47
Design Considerations: Prosthetic Foot

So, we are looking at assistive devices and specifically we are looking at a Prosthesis under narcosis. So, prosthesis is a replacement limb, orthosis is a supportive device and we are looking at a lower limb prosthesis and orthosis to understand based on our knowledge of normal human walking. What would be some of the requirements design requirements in order to be able to enable a person who uses one of these devices to have as functionally as much as possible in terms of say walking, standing etcetera sitting, etcetera.

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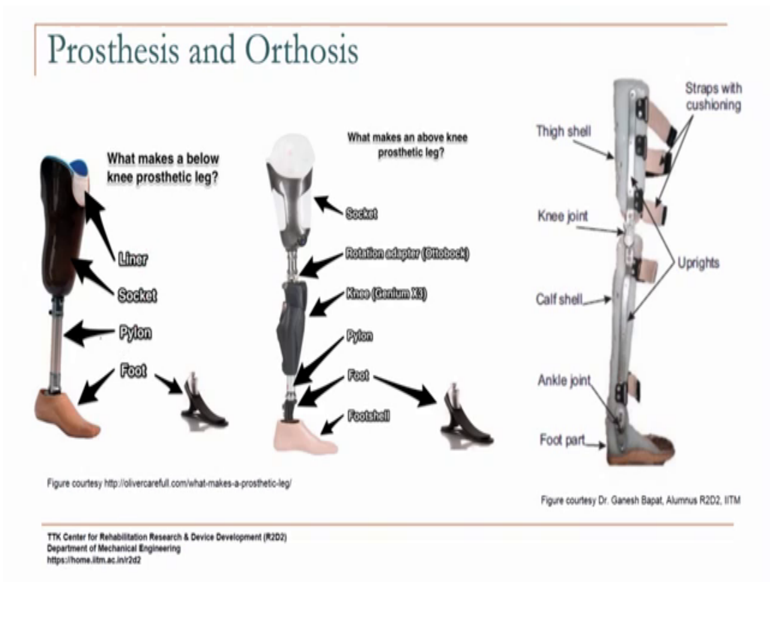

So, we saw that in a below knee prosthetic leg, you have a liner, a socket, pylon is your load bearing member whose height can be adjusted depending on the length of the residual limb of the person. And then you have a prosthetic foot which, on the outside may look like an actual foot mid, it may be made of foam, it may have a foam cover or a foam foot shell and look can be colored to match the person's other foot. But on the inside actually you would have various types of hardware in there and that is what we are going to look at today to see what are why are these prosthetic feet, why are some of them designed the way they are you know what are the functions that we are trying to replicate.

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So, we also saw that so, this is a prosthesis, but the foam cover you may or some people may prefer not to use this kind of a foam cover especially if there are more joints. So, if if you have an above knee prosthesis and you use a foam cover that could affect the functioning of the knee that is inside the prosthesis.

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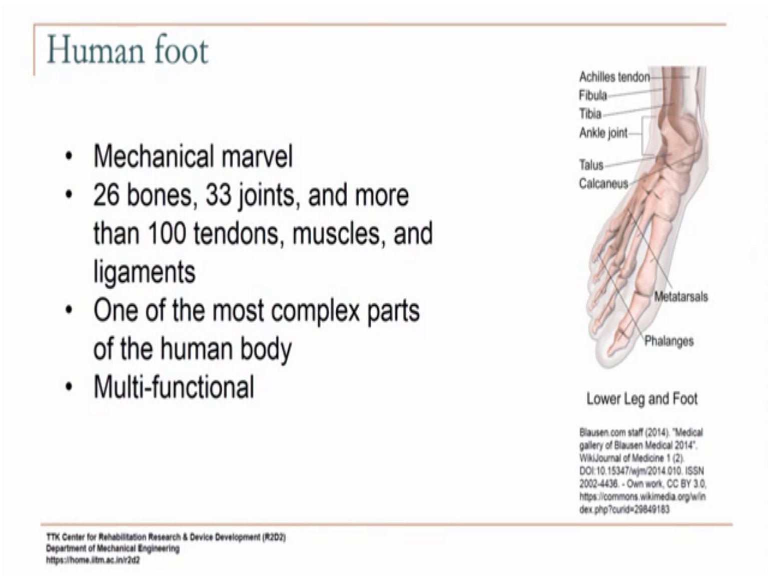

But we saw that the human foot is a very complex mechanical structure. Lots of bones ligaments tendons and muscles that act together to make the foot perform the way it does. And if trying to create a biomimetic foot, something that looks like the human foot can be very very difficult or structurally similar; you know with so many different parts, it would be a nightmare from a design perspective to control so many elements, so many joints etcetera ok. You know without noise and all that.

So, that is the; so, what we try to do is, we try to understand the function of the foot and then what we will attempt to do is you know, we look at the designs and see how they attempt to perform the functional requirements of the foot.

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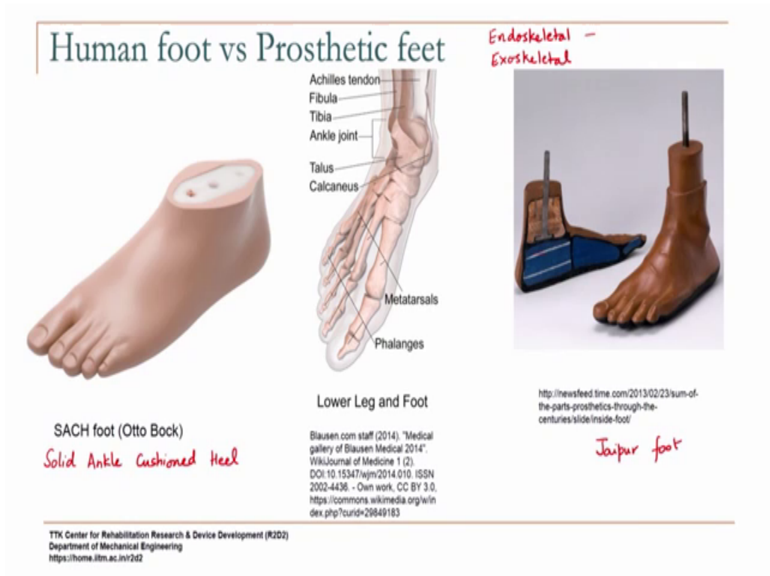

The prosthetic feet on the outside may look similar to a foot, but like I said on the inside structurally they could be quite different. The simplest type of foot one of the simplest type of feet is what is known as the solid ankle cushioned heel. So, this is s SACH stand for Solid Ankle Cushioned Heel and this particular foot is one made by a company called Otto Bock. And then on this side, you have the Jaipur foot which is more for the Asian and African populations. It is very popular in developing countries because functionally it provides more for the conditions that we encounter in these countries ok. In the western countries normally a person wears shoes all the time ok.

So, the prosthetic foot is always housed in a shoe. So, they are walking with it so, it is not subject to the same kind of harsh conditions, where you know where in countries like ours a lot of people we walk barefoot especially more in the rural areas right. When you know if somebody is on a farm or you know walking just the terrain anywhere is much harder to navigate and so, this which uses types of rubber in different parts of the feet and it also has a solid wooden block here through which a bolt goes to attach through to the rest of the prosthesis ok.

So, you can have either a modular or so those are called an endoskeletal or an exoskeletal design. So, in prosthesis you have endoskeletal or exoskeletal prosthesis. In the endoskeleton prosthesis, the inner components like you have these modular components that basically perform the function of the load bearing that are encased by some kind of a cosmetic cover. In the exoskeletal type of prosthesis, it may be say fashioned out of wood for instance or nowadays they use high density polyethylene pipes that are shaped and it so, it forms the structural member as well as the shape of the leg. It provides both the exoskeletal prosthesis.

So, the load bearing is done by the member that is shaped like the leg ok. In the endoskeleton, you have some inner members that are covered by a cosmetic cover that is shaped like the leg. So, some of these feet can be used with exoskeletal or endoskeletal prosthesis. So, this kind of a bolt may go into you know, it can go into some adapter to which you have other endoskeletal components attached and then it may have a foam cover. Or it could go into another block of wood that is then, shaped like you saw earlier. You saw some prosthetic legs that are made out of wood or other materials. So, these are some other types of prosthetic feet.

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So, if you look at the internal structure, you will see some of them may have some kind of an ankle. The ankle could be a mechanical you know, it could just be a mechanical ankle with some bumpers or some cushioning material or it could be with hydraulic. You have anchors that are made with dampers that use magnetorheological fluid. So, there are various kinds of devices that could be designed. Here you can see that you have layers of leaf springs ok. So, you get graduated resistance, you get increasing resistance as the foot bends ok.

So, as you go load the toe, the resistance to the loading keeps increasing because more of the springs come into play as you know that this is a simpler form where there is only one toe spring ok. So, this part is typically called the keel of the foot; this part. They have some of these; these are called pyramid adapters this is a very standard form of attaching endoskeletal components. So, you have a pyramid; you will have a pyramid and a pyramid receiver ok.

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You have the foot as a pyramid and you see this the pylon has an adapter attached to it which is a pyramid receiver. So, you can see there are 4 holes on the receiver and you have 4 set screws. So, if you look at this you see that the foot has a pyramid on top like that and then the pylon has this pyramid receiver. And if you look at the attachment the receiver has 4 holes into which there are set screws that go and you have the flats on the pyramid. You have the 4 flats, you can see here in this diagram. You have these flat surfaces right, you have four of them one on each side and the set screws go and lock into lock on that surface ok.

What this allows you to do is, it allows you to change the tilt of the foot in two different planes. Because I can loosen one set screw tighten on the opposite side and that changes the angulation in that particular plane ok. So, I can adjust the plantarflexion, dorsiflexion or the inversion eversion in the foot. So, this provides; if I want to align the foot to a particular heel height for instance, what the person is going to do? I can use these set screws to adjust the level of the foot ok. So, it is called yeah I mentioned earlier that alignment is basically how the spatial arrangement of these components relative to each other and this kind of a an adapter provides that ability.

If you look at the top of this pylon ok, that goes into what is called a tube adapter. So, this tube adapter basically has a slot and again a set screw. So, what that helps you to do is I can now change the rotation of this foot with respect to the direction of progression.

Remember as we walk, we generally have a slight toe out angle ok. So, having these sort of adjustments is necessary. In an exoskeleton prosthesis they try to make it so, that all this is built in from the time that they built it. But the problem with that is if you do not get it, then it is difficult to change.

So, endoskeletal prosthesis give you that ability you can change alignment. It is so they may first put it together in a fixture and then ask the person to walk with it ok. So, the first part of it is called static alignment, then as the person walks; they will observe how the walking is and then they may need to make changes to the alignment using these sort of adapters. So, this pyramid system is a pretty standard system used in endoskeletal prosthesis.

So, across manufacturers they tend to follow the so, the pyramid and the pyramid receiver are fairly standard components. You can get them from different people, but they will kind of like it nuts and bolts right. Once you specify so, this for prosthesis it is a pretty standard component. If you take a pyramid, you use it with someone else's pyramid receiver; it should still work right. So, and these pylons are also come in standard dimensions. They have various standard dimensions and so, you know that they are interchangeable. You can use parts from different places. So, the key to an effective design is basically to understand the function of the prosthesis.

So, we know that a prosthesis is a replacement ok. So, we need to know what is the function of the limb that it is replacing and it is more important to understand what that function is, rather than how the human body accomplishes that which is why I was talking about the difference in the design of the human foot versus design of a prosthetic foot. The human foot accomplishes certain functions with a particular design, but that design replicating that design may not be the best solution; biomimicry may not be the best solution.

So, you want to maybe mimic the function of the biological foot, but perhaps not in the same manner. So, you have to be creative about and for that you first need to understand what the function is rather than how the body is accomplishing it. And in many cases; so, as in the case of a prosthesis you know that not just the limb, but a lot of other structures that make the far limb function the way it is are missing. A lot of the muscles ligaments for you know the anatomical structures are also missing right.

So, there may be need to have some compensatory effects that are built into the prosthesis. So, for instance in a passive prosthesis, all the control for the prosthesis is happening through the residual limb in the socket. Different people may have had their amputation at different levels. And so, the strength of their residual limb, their ability to apply moments or you know the strength of the residual limb can vary quite a bit ok. But you know you have a prosthesis of a say certain mass in order to be able to provide the user the ability to control that prosthesis. There may need to be certain compensatory effects that are built into the design of the prosthesis.

It may be at the foot level, it may be at the knee level for an above knee prosthesis or a combination of those that may need to be. Because ultimately the primary function is you want to be able to restore independence to the user ok. So, how we do that is what differentiates this design.

So, if you think about a lower limb prosthesis, what are the primary functions that it has to perform. So, a person who is lost a leg could be at the trance to be a level or the trance ephemeral level. So, the first primary function is being able to stand ok; stand in a stable fashion and then perhaps walk in a stable fashion. So, the components that you put together should provide this kind of stability. Walking as you know is a series of periodic impacts with the ground ok.

So, some amount of shock absorption is necessary in the prosthesis because without that what is going to happen, every time the person walks every time there is an impact with the ground that is going to be directly transmitted to the rest of the body. And so, the person may start developing secondary problems. They may start having hip pain you know, if the hip is constantly being impacted we start having back pain because all the shock is now being transmitted to the sorry the rest of the body that is from the residual limb. So, you need some kind of a mechanism some kind some mechanisms again it could be in the foot, it could be in the way the knee functions, it could be in the socket liners that you put you know the cushioning material between the residual limb and the socket.

But there are some mechanisms that need to be provided for shock absorption. Then if it is the person should also be able to sit comfortably ok. So, the manner in which the prosthesis is attached to the body you know, if you have bells or if you have other things or if you have a knee joint, that knee joint should allow for comfortable sitting.

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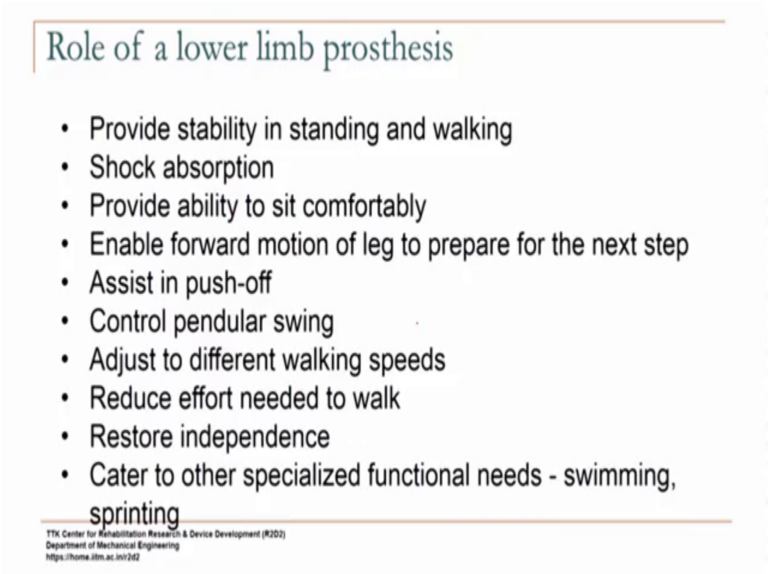

And the sitting may not just be in you know on a chair ok. Depending on the cultural needs cultural needs the setting may involve sitting cross legged on the ground. You know if in a community everybody tends to sit cross legged on the ground one person alone says, I need a chair. See essentially a person with a disability does not want to stand out. In many cases, they want to be able to fit and resume their normal lives.

So, some of the demands may be that this knee should be if they have a prosthetic knee, it should allow them to sit comfortably. It could be sitting in a chair sitting in a chair, you can you know you have your knee flexion at about 90 degrees you are ok. Try to sit in a small Maruti car, can you keep your knee at 90 degrees? No, you would have to bend it even more or if you want to pray in some religions kneeling down is a necessary requirement.

So, again so, depending on the socio cultural needs providing the ability to sit or squat or kneel comfortably may also be part of the requirements. It is a different matter whether all the prosthesis provide all these functions because as I said the human body is very versatile. It can adapt to different situations like when we talked about the foot right, you can grasp something with the foot like when you are climbing a tree you know your soul can actually grasp. But trunk of the tree or you can make it completely rigid, if you are standing on tiptoe.

But a prosthesis may not be able to have the same level of versatility and it there may also be a cost factor involved because the more functions you try to design ok, the more complex the design may be and therefore, the cost may also go up. So, those are all design criteria that start to come in, but functionally you want to be able to provide the ability.

So, now we are not talking let us not talk about costs and other constraints, but what should the prosthesis really do ok? How they accomplish at in different levels, we will see later. Then as you are walking one of the things the limb has to do is to swing forward right to prepare for the next step. So, enabling that you know so, the knee bends and swings forward. So, enabling that swinging such that by the time it is ready for the next step; it is the knee is fully extended that is an important criterion for forward progression.

So, stability during stance, limb advancement during swing; we talked about this during and we talked about walking. Some kind of assistance and push off ok; so, if you are talking about a prosthesis user that person even if it is a below knee prosthesis, you lost the connection you know the Achilles tendon, the gastroc and soleus muscles that action is now gone ok. So, if you look at so, how do you provide some kind of which was what was assisting in pushing off from the ground? If that mechanism is now gone, you need to have some other kind of a mechanism in the prosthetic foot to enable walking in that manner.

Then when you have the swinging of the leg right; when you swing the leg forward, there is muscular action controlling that pendulum like swinging of the leg. So, gravity is causing it to move down, but it is moving in a controlled fashion and it also adapts when you change your walking speed ok. So, if you have a prosthetic knee, then you know is it able to adapt to different walking speeds. Is it able to appropriately because towards the end of swing your hamstrings start acting to dampen the extension. So, that you do not have that shock of hitting full extension right. So, things like that have to now be become part of the functional requirements of a prosthesis. Overall you need to reduce the effort needed to walk.

So, here you have you have lost a lot of muscular control muscle control, joint control and it is like carrying an additional weight on your residual limb; if you look at the prosthesis ok. So, in many cases it so, happens that the effort required to walk with the prosthesis is higher than for normal walking and this is in spite of the fact that many prosthesis are lighter than the leg that they replace. Why should they be lighter than the leg, they replace? Because you are you do not have the powering, you do not have the muscles to power the prosthesis. So, your power is now limited.

So, you have to the prosthesis should be light as light as possible of course, that is an area of active research because one it has to be able to withstand the loads that its subjected to. So, you cannot make an extremely light prosthesis and also a very light prosthesis affects the swing. See because you are using the inertial properties of the pendulum swing for forward progression, for limb advancement that is dependent on the mass of the shank.

If you have it too light, then it may take too much time to achieve full extension to prepare for the next step. So, there is a balance that has to be struck between these two competing requirements. But overall for a person to be able to successfully use the prosthesis, the effort should not be too much ok. The effort to use the prosthesis because then, the motivation to use the prosthesis will go down ok. So, the person will not be able to walk comfortably. Then other there may be other functional needs. So, a person may want to play certain sports and this is especially true you know standing and walking alone may not be enough ok; if you are talking about children. If you are talking about young people who have their entire lives ahead of them, for them to stay fit, they may want to play some games they may want to do other things ok.

So, just standing and walking may not be sufficient. So, a prosthesis that enables them to do more will give them greater independence greater self esteem and enable them to integrate more easily. So, you give a child a prosthesis and the child can say run around and play with other kids it is a huge difference, then just a prosthesis which would allow that child to walk because playing is what children do best ok. So, something that allows them to resume that kind of a normal life and integration into their community and society will help. So, that is also something that; in some cases it may be a very specialized prosthesis.

So, for swimming you know like you have the webbed feet something like that or a waterproof prosthesis. So, it may end up that a person uses a different prosthesis for that particular activity because again what they use for everyday life may not really do the job for the specialized activity and the prosthesis they have for the specialized activity may not do the job in everyday life, like you saw with the sprinting leg with just the spring. It is hard for somebody to stand and walk on a leg like that on a spring like that ok, but for sprinting where you are on your toes you know, then that is a good that provides the functionality for that particular activity.

So, understanding the needs of the user is very critical. Unfortunately because of cost reasons many people may not get a prosthesis that is able to do everything that they need to do. So, if you look at muscle action at the foot and ankle during gate, then what you see is initially you have, what kind of action do you have here?

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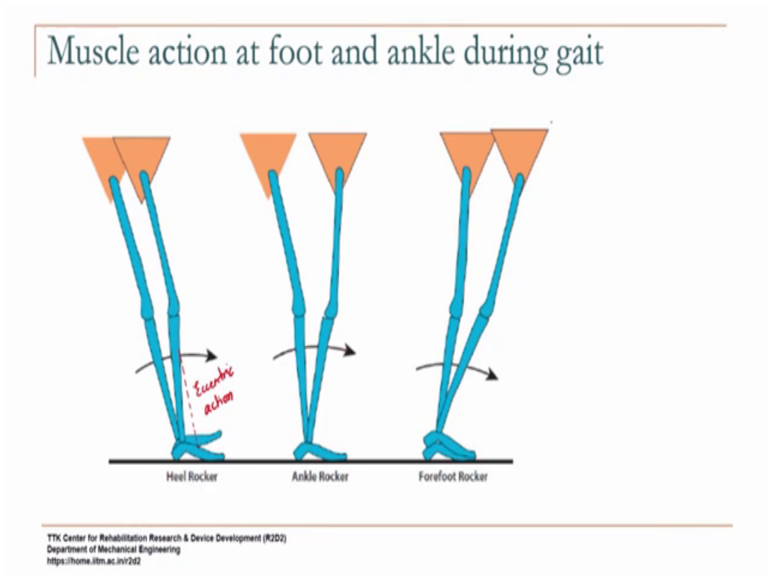

Your tibialis anterior will undergo eccentric action right to the dorsiflexors, the ankle dorsiflexors at two; so, that at the heel rocker, the foot is lowered to the ground gently. You do not have foot flat ok.

So, you have to have some way of accomplishing. So, you want to have foot flat, you want to have foot flat. So, you want to have that eccentric action so, that something the foot lowers to the ground gently. Then here you have in the ankle rocker portion you are moving about the ankle ok. So, the entire limb is advancing over that ankle. The foot stays on the ground and then in the when you move to the forefoot rocker that is when the gastroc and soleus, the calf muscles start acting strongly to propel the leg ok. So, if you look at so, a prosthetic foot should at the minimum enable this foot flat enable it in a controlled fashion and there is one more thing that happens here, at heel contact you also have some kind of shock absorption ok.

You have, all of us have heel pads that are that have a lot of cushioning in them; if you if you feel the heel you can feel that there is some cushioning that is built in to the structure ok. So, that is another function that the prosthetic foot has to perform. So, the simplest kind of design that came up is the solid ankle cushion heel foot back in 1957.

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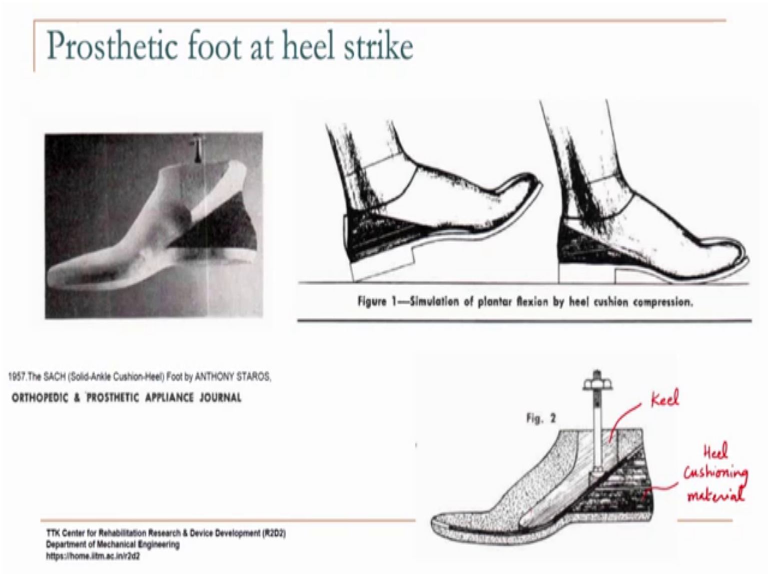

And what they essentially did was they put some kind of a wooden block like this. So, this is the keel of the foot and then they put some kind of a cushioning material at the heel. And what that does is so, but the ankle remains solid. See one of the reasons for keeping the more joints you have ok, harder it is to control it also becomes a maintenance issue ok. So, the simplest design said let us you know we want to simulate this plantar flexion for instance a control plantar flexion. Let us instead of putting an ankle in there and then trying to figure out, how to put a tibialis anterior and an achilles tendon kind of an action in it. Let us make the heel out of a cushioning material and make the heel out of a cushioning material and a solid keel ok.

So, this is made up of wood in this case so, that is used to attach the foot to the rest of the prosthesis, but it is essentially a solid ankle and then of course, the foam that surrounds this hardware also has some compressibility ok. So, you are looking at flex providing flexibility in the foot by means of the outer structure of the foot and then at the heel alone you put some additional sort of cushioning material which is of a different stiffness depending on the say the weight of the person ok. So, a person who is very heavy would need a stiffer heel and a person who is very light would need a softer material in the heel.

So, that they experience that shock absorption at heel contact at heel contact. And then as that heel compresses ok, the foot lowers to the ground. So, it helps the foot to lower to the ground. So, this is a maker mechanism that is different from how the human foot does it ok, but this is the simplest kind of prosthetic foot by compression of the heel cushion, you get that controlled plantar flexion. So, you do not have any muscles in the front now right you have a solid ankle. So, the angle of, the ankle does not change, but the foot by means of the materials use compresses and enables this.

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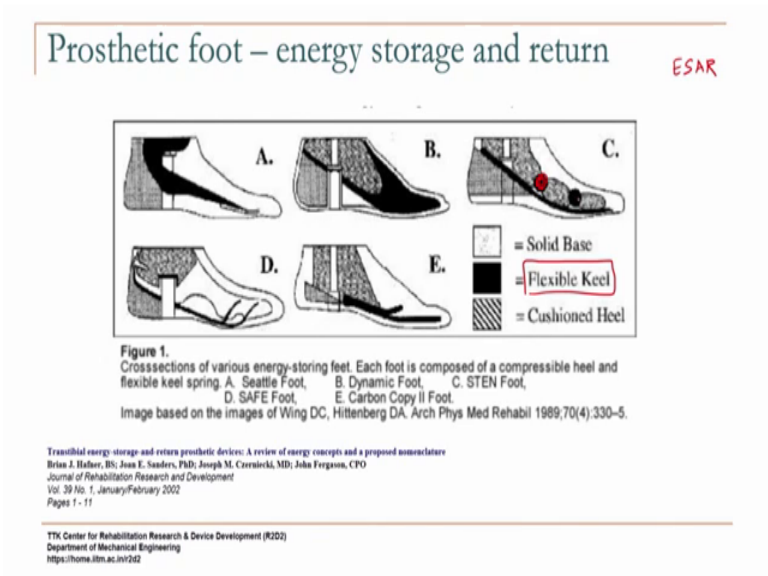

Then the next generation of feet said we can do more ok. So, in the SACH foot, there was like a belt that went from a stiff belt that they would have from the heel to the toes of the foot that would provide some kind of resistance as you rolled over the foot, but not a whole lot. So, it was just a belt made of some thick material. It was a flexible belt which would the idea was to allow that rolling over the foot. Other designs, then said I we can do better ok.

So, for instance and these were feet that are called ESAR, Energy Storing Storage And Return feet. So, what they try to do is they would have many of them have a cushioned heel to enable that, but in addition to that they started making this keel like a spring; like a spring of this nature. So, that what happens is when you get on the toe ok, the spring starts compressing and when it tries to return to its position, it is providing that thrust. It is providing that push off. So, you are using a passive spring basically to perform or at least try to perform the function of the calf muscles, the triceps. Say there are different configurations they use there. So, this becomes now a instead of a solid keel, you who now have a flexible keel in these type of prosthesis and then in you also have a cushion heel

So, in these designs; so, here you actually have a foot that has some kind of a connections between so it has multiple parts which are then connected together by some flexible material. So, it is not a joint in the it is more of using flexible parts to connect. These are the flex different stiffnesses in different parts of the foot which is actually what if you see the Jaipur foot that is also what also tries to do the same thing it has different stiffnesses in different parts of the foot. Then in this foot for instance, you have the so, if you are walking fast or if you are walking fast, you will let tend to load the forefoot more.

So, the idea is you get additional you increase the stiffness of the spring by because once this bends to a certain limit, then this spring is also now engaged and so, the push off that you get will be more. So, that is the, and then you have others that are shaped in a more fancy. So, different manufacturers have tried different designs for these kind of energy storing and return feet. So, this was the next generation of prosthetic feet. Many of these as you can see have the cushioned heel and this again. So, both the keel and the heel would be customizable.

So, the prosthetist who is the person who fits these artificial limbs would specify to the manufacturer that I want a foot of I want a left or a right foot, particular size, particular color depending on what options are available. And then say the manufacturer would have recommendations based on they say the weight of the user. They would say for a person who is about 40 to 50 kg's; we recommend a soft heel. So, they may have these heel pieces in different stiffnesses and they would recommend that for a person of this weight this is what we recommend.

Then for the again for the toe they may have depending on they may vary the thickness of this keel they may mold these skills in different shapes. Again like readymade you know like your shoes or something like that they custom; it is somewhat customized, but not totally ok. So, it is like picking different options to put together this kind of a foot for a particular user. So, they would have different keel stiffnesses, different heel stiffnesses to suit the particular user.

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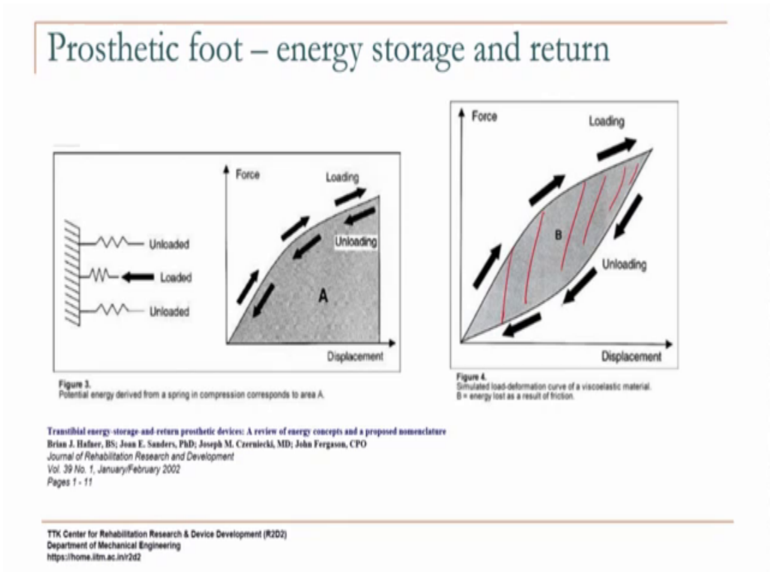

So, if you look at the prosthetic foot, then it basically you know a keel, a flexible keel acts like a spring ok. Now if it was an elastic spring then, as you load it deforms; as you unload, it will return the same energy. But in this case we are actually talking about these materials which are more viscoelastic. So, there is always some hysteresis and also you have the form of the outer cover, outer foot which is also viscoelastic material. So, combination of that ends up being there is some energy loss. So, the entire energy that was, so it follows more a curve like this in the loading. If you look at the force displacement curve, if this is the loading curve; the unloading curve results in like this and this area in between represents the lost energy in terms of heat because of friction between the parts ok. So, this is the characteristic of these energy storage and returned feet.

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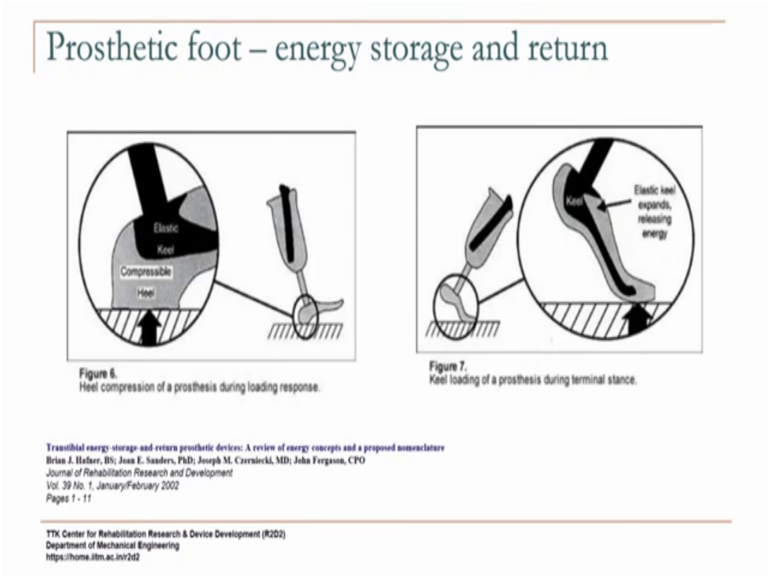

Here is another it shows the compressible heel which enables the foot flat and then in the forefoot, you see the elastic keel. Once it is compressed because it continues to get compressed through mid stance and forefoot loading ok. The keel gets compressed and then once it is compressed to a point and the other leg has taken over the weight bearing. So, now, then this foot is now it is releasing the energy that was stored in the spring and that provides that push off to some extent. So, here are some different prosthetic feet.

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Another popular foot so, these are more of the prosthetic field that are used by athletes. So, you see here this actually has a shock absorber ok. Similar to the shock absorbers in mountain bikes and all that it has a shock absorber. It is a new you can actually put a pump to it and you know change customize it to your needs. So, if you are going to go for a run you would pump more air into it. So, that you get better shock absorption if you are walking you will basically let out some of that here.

So, you it actually comes with a pump and just like you are a volleyball or basket ball comes with its own valve and you can connect it to a cycle pump and do it. This one also has a similar mechanism. These are springs that are made of carbon fiber and so, these are composite springs made of some composite materials and then this particular foot that is shown here has like a dovetail adapter ok. And what that helps the prosthetist do is, they can change the AP location, anterior posterior location of the foot. So, depending on the activity level of the person, they can change the stiffness of the dough by changing that the anterior posting.

So, again this is another aspect of alignment that may be provided in certain types of components because for prosthetic feet especially that AP alignment can make a big difference in the way the person walks then this is a multiaxial foot. So, inside it actually has it enables movement in all three plane.

So, it is made of some kind of a compressible material that allows movement in all three planes. So, something like that would be useful for say walking on uneven terrain. So, if you spend a lot of time on uneven terrain, then you want better confirm. So, the split design also for the toe that you will see in some prosthetic feet is to again accommodate for uneven terrain as opposed to just a flat plate when you are walking on rocks or you know when you are walking on; if it is not flat ground. It gives you that little bit of inversion eversion. So, you see all this is being done passively and in controlled fashion. All the control is happening because of the stiffness of the materials used because the more joints that you put in you know joints that are movable; it can become a maintenance nightmare.

So, a lot of this movement is happening because of the passive structures. Here again in the Jaipur foot, they go about it in a different way. So, they use the rubber of different stiffnesses in different parts of the foot. The heel will have a softer rubber and then they have a skin, the skin is also made of a different type of rubber ok. So, the skin is also made up of and that and in the bottom you actually have tire tread you know, similar to what you have in tires you have rubber that has; so that for walking barefoot, it is very durable.

So, these sort of feet if you look at these foam polyurethane foam feet, they would not last very long, if you walk barefoot with them. They are designed for walking with shoes whereas, these feet you know people walk in muddy water, they walk on fields, they walk everywhere and it holds them because it is again made up of really strong rubber similar to what they use and tires and it is made.

So, the single access foot actually has an ankle joint. So, there is a bolt. So, if you look at the keel, it is shaped like this it has a pyramid adapter and it has a single bolt running through that. So, it is basically a hinge joint that allows dorsiflexion plantarflexion. And the stiffness you know how much dorsiflexion these resistance to the dorsiflexion and plantarflexion is provided by these bumpers that are; so, they are like urethane bumpers that are placed in that foot. So, it is assembled together with these bumpers.

So, that then you dorsiflex, there is some resistance to that. When you plant a flex, there is some resistance the single access foot is used a lot for people with an above knee prosthesis because what it does is because there is actually a degree of freedom at the ankle. It enables easy foot flat as opposed to foot flat that happens only because of the compression and the heel.

So, because there is an actually joint, it enables quick foot flat which is necessary for a person with an above knee prosthesis in order to control the knee better so that you get the base of support and also it helps to move the load line in front of the knee; so, that you can lock the knee more easily. So, single access foot sometimes is used by people with an above knee amputation.