Panel Discussion

Multidisciplinary Approaches to Limb Loss: A Chain of Events Leading to a Single Step

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It's an honor to be here.

In my research program, we think about the biomechanics and control of the whole organism—the whole body—down to the individual muscle cell, and we apply these sciences to the development of various technologies: prosthetics, orthotics, and also exoskeletons for human augmentation.

Today, I'm going to speak primarily about leg prosthetics, but a lot of what I have to say is also appropriate for upper-limb amputees as well.

I'll begin with a project that has been underway in my laboratory for many years, and it has been completed. It's now a product. And then I'm going to spend the rest of the time making fun of that device and telling you what's wrong with it and what we need to do as a community. The device is a transfemoral external knee prosthesis. We call it the Rheo Knee™ System (Össur, Reykjavik, Iceland), because it uses magnetorheological fluid.

How does it work? The device contains carrier oil and small iron particles suspended in that carrier fluid. We modulate the magnetic field inside the knee, and by doing so, we can vary knee resistance, or damping, quickly and quietly. So, this is a variable damping technology.

We recently compared the Rheo to two systems that have been on the market for quite some time: the Mauch S&S® (Mauch, Dayton, Ohio), a passive hydraulic system, and the C-Leg® (Otto Bock, Minneapolis, Minnesota), which we all are familiar with. The C-Leg® is also a hydraulic unit, like the Mauch, but it's controlled by a microprocessor. In the study, we found that the amount of food energy the above-knee amputee requires to move from point A to point B is affected by these distinct knee designs. We got a small but significant effect with the Rheo, a reduction in metabolic cost or an increase in walking economy. We've looked into the biomechanical mechanisms that might explain this difference, and what we've found is that the Rheo, because of its different strategy for developing knee resistance or damping, is able to reduce the muscular effort at the hip on the affected side.

In terms of control, the Rheo knee is fairly adaptive. It often does not require a human to program the knee to the patient. The knee adapts its damping parameters to the patient, allowing the patient to walk at different speeds and across different terrains. The Rheo essentially does experiments and optimizes itself to the patient.

Patients with a dumb knee, with no computational intelligence whatsoever, no sensors or whatnot, will have a highly pathological gait for ascending or descending stairs. This is true even for patients who have adapted quite well, whose unaffected, biological limb is quite strong.

With the Rheo, patients are able to walk up steps foot-over-foot. The knee recognizes that patients are going up steps and outputs the appropriate algorithm. Patients are also, of course, able to go down steps. Recently, Össur, the second-largest prosthetic manufacturer in the world—they're in Iceland—launched the Rheo as a product. It's now available to amputees throughout Europe and the United States.

Rheo Knee™ being used on uneven ground

Moving on, now I'm going to make fun of what I just told you about. What's the opportunity for making advances in this area? What are the issues?

Commercially available above-knee prostheses are variable damping mechanisms. What do I mean by this? I call them fancy car brakes. All they're able to do is dissipate mechanical energy.

The human knee is capable of dissipating mechanical energy, but additionally it's capable of actually supplying a motive force or torque and also acting like a spring and varying its stiffness. We need to do better in the prosthetic knee department.

In the foot/ankle department, current commercially available systems are completely passive, typically spring, devices. In a Flex-Foot design, you don't see an actuator or sensors. Therefore, the system has no ability to adapt to the amputee.

Biologists tell us there's a lot going on in the healthy human ankle. During the early stance phase in level-ground walking, even at a constant walking speed, the stiffness of the ankle is constantly being updated by the central nervous system. In late stance, the ankle supplies a tremendous amount of positive power, a motive moment, which is believed to be very important to human ambulation.

Given the passive nature of today's commercially available prostheses, how does that affect the patient? It causes a pathological gait, a limp, which typically causes excessive impact forces to the musculoskeletal system, which can trigger difficulties later in life, i.e., back problems and whatnot. Normally, amputees also require a greater amount of food energy to go from point A to point B, substantially greater. The Rheo knee improved that somewhat, but we have a great deal to go from here.

To really push this area of medicine, we need to merge body with machine, to create an intimacy between the human body and the prosthetic device.

In the interest of time, I'd like to describe two key areas, although other critical issues exist. First, we need better motor systems, better actuators that are muscle-like. Second, we need distributed sensing and intelligence.

Beginning with muscle-like actuation, why are muscles so fabulous? Why do we desire to have muscle-like actuators? Muscle tissue has excellent functional characteristics. It's very mechanically powerful given its size. You can typically get 50 watts per kilogram of muscle tissue for continuous operation.

And muscle is functionally adaptive. We all know this. If we're couch potatoes and we do not exercise, then our muscles become weak. But if we work out, they scale to the task. Muscles are very scalable. They're in small critters all the way up to blue whales. Muscles are quiet, too. If we were all humanoid robots in this room, powered by a synthetic motor system, gasoline-powered engine, electric motor, whatever, we'd raise a tremendous racket and barely would be able to communicate.

Noise is a really important concern and it's a difficult problem to solve. Could we use muscle tissue in our robots and prostheses? Sounds crazy, but in my group we're actually thinking about this idea of hybrid devices, where part of the device is living tissue and the remaining component is synthetic.

We've built this swimming robot. It's swimming through its own media, which comprises antibiotics, antimycotics, and also glucose to feed the muscle tissues.

So, we might want to think that someday, the prosthetic hand, for example, would be this hybrid device in which we'd use synthetic components only where synthetic components are better than biological components.

That's a hard problem, obviously, and it's going to take a few years to solve. In the short term, what do we do? Now, I want to talk about actuator systems that are muscle-like to some degree.

Several years ago, in the field of robotics, my friend and colleague Gill Pratt developed what's called the series-elastic actuator. It's muscle-like in an abstract sense because what you have is an electric motor in series or next to a compliant spring, kind of like a muscle belly in series with a tendon.

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To control the device, we sense the amount of energy that's stored in the series spring, similar to an artificial golgi tendon organ, and the control system basically controls how much energy is in the series spring or the spring deflection. By doing that, we can accurately control the forces that the system exerts on the world. It's very shock-tolerant, and very force-controllable.

This was originally developed for legged robots. We have a dinosaur robot we call Trudy that is autonomous, carries its own power supply, and walks in 3-D space. Trudy uses these series-elastic actuators. Recently, we've also used the actuators for rehab in my group. We had a gentleman who had suffered a stroke. He had this classic drop-foot condition where the muscles of the anterior compartment of the leg were weak, so he'd hit the ground on his left side with his forefoot instead of his heel.

We developed a robot that wraps around his leg that pushes on him and restores his gait. With the device, there's a better symmetry between affected and unaffected sides and he's able to walk at a faster speed.

That's one possibility. But this system relies on electric motors. Electric motors are not silent. They're better than gasoline-powered engines, for sure, but you can still hear them.

Electric motors also require a power supply. We're often constrained to use battery technology, which has a rather poor energy density.

What about artificial muscle? This doesn't help us in the efficiency or the transduction efficiency arena, but it may help us in terms of the fact that artificial muscles are linear and they're also very quiet.

There is a series of muscles, electroactive polymers, that has been developed by SRI International in California, by Roy Kornbluh and his colleagues. In my view, their artificial muscles are extremely impressive.

They've done sort of a finger-type embodiment. It's activated by applying high voltages. They've already used the muscle in biomimetic-type robots. They also have a giant fly, where the muscles are distorting the thorax of the machine, which flaps the wings. The fly can actually get off the ground, but they have no idea how to control it.

What are the remaining issues? One is a scaling issue. At SRI, they're very good at building muscles the size of your middle finger, but to build a gastrocnemius is more difficult. Also, there's a cycle life issue. If you keep the strains very modest, just a few percent, you can get a million cycles. However, at physiologic strains of 20 percent, the muscle breaks down quickly.

The muscle requires high voltage, as I mentioned, but if you keep the currents very low, a human can safely interact with the muscle. This is exciting, and I believe researchers in this area will solve these remaining problems.

So, we have muscle-like actuators, and that's indeed important. But how we use the muscle actuators, the muscle/skeletal architecture, is also critical.

It would indeed be a mistake to simply put one motor per degree of freedom. In our body, as we all know, some of our muscles span a single joint and some muscles span two joints and other muscles, polyarticular muscles, span more than two joints. Biologists tell us that this is important for having lightweight limbs, especially distally. Polyarticular actuation is important to have muscles that are proximal that do work and exert control distally.

I'm going to quickly take you through a walking step and give you a sense of how this works and why it's important. A typical walking step has seven stages, from heel-strike to toe-off. At stage three, the hip extends, which, since the foot is on the ground, straightens the knee. As the knee straightens, since we have the gastrocnemius that spans both the ankle and the knee, and that's linked to this massive tendon, the Achilles tendon, that action of actively extending the hip using hip extensors actually pumps energy into the Achilles spring. Then that energy can, in turn, power the ankle. This is very intriguing because we can think of an above-knee prosthesis in which we actually harness the muscles of the amputee and we use those energies, we transfer those energies past the knee to power the ankle. That's very compelling because in principle one could do this with very small motors and variable damper and passive spring systems. This approach would lead to a low-mass, fairly quiet system. Again, it's not only the muscle-like actuators but also how we use them that is critical.

I'm going to finish with distributed sensing intelligence. Again, I'm going to make fun of my own design. The Rheo is adaptive and it adapts because it knows something about walking—biomechanical knowledge—and it knows something about how prosthetists can adjust alignment and knee resistance to get an amputee to walk better. But the knee doesn't have a direct measure of what the person wants, the user intent. With the Rheo or the C-Leg, or all these systems, the amputee has no way to tell his or her knee that there are stairs up ahead, or there's a pothole.

Rheo Knee™

We, too, are beginning to work with the Alfred Mann Foundation, and—as we all know—they've developed this wonderful technology called the BION. We just heard a talk about functional electrical stimulation (FES), where the BION can be used to control skeletal muscle. We can also think about the BION as a sensor. We can implant the BION into muscle and measure the extent to which the spinal cord has depolarized a muscle cell.

We recently conducted an experimental session. I got wired up, and we measured my electromyographic signals from my residual limb. Another participant, Sam, wore a Vicon motion-capture system where we measured the state of Sam's leg as he moved his foot/ankle system. We're taking that data and trying to develop models to link the electromyographic signals to my desired movements or biomechanics.

Our plan is, about a year from now, we'll inject BIONs into my residual limb, and then we'll apply these algorithms. When I think about moving my ankle, plantar flexing and dorsiflexing, I'll look down at an active ankle we've developed already in my laboratory that will respond to my movement desires.

This will be very important to the amputee, who will have an active alignment control for going up and down hills and stairs. It will also dramatically increase the dynamic cosmesis of amputee gait. Just a note here: Another very exciting technology that is more preliminary and has not been fleshed out yet is the sieve electrode. One problem that we're going to face is this issue of an afferent sensory signal. With the BION, I'll have my eyes, my visual system, to look down and to tell me what the position of my ankle is, roughly. And we'll perhaps embed tactile vibration into the socket to give me an additional afferent signal.

What would be fun is to think about the sieve electrode where we transsect a peripheral nerve and we get it to grow through the electrode. With this, you have bidirectional controllability, in which you can actually close the loop.

Imagine a future with this type of technology that an amputee would not only be able to walk across a sandy beach but also could actually feel the sand against his prosthetic foot.

I'd like to thank my various sponsors. We are beginning to work with the Department of Veterans Affairs (VA). In the future, the Alfred Mann Foundation will supply us with BIONs and engineering support. The Defense Advanced Research Projects Agency (DARPA) is also a contributor to this work and other projects in my laboratory. And, as I mentioned earlier, Össur, a for-profit manufacturer of prosthetic components, helped us in the artificial knee development.

To summarize, advances in muscle-like actuators, neuroprostheses, and biomimetic control strategies are necessary to increase the merging of body and machine to create an intimacy between the human body and prostheses. It's our thesis that such an intimacy will create a paradigm shift in this area of medicine. Thank you very much.

Bio:

The science and technology research accomplishments by Hugh M. Herr, PhD, have already had a significant effect on physically challenged people. The Variable-Damper Knee Prosthesis has recently been commercialized by Össur Inc. and is now benefiting transfemoral amputees throughout the world. In addition, the Active Ankle-Foot Orthosis is now being commercialized and has the potential for improving the quality of life of millions of stroke patients in the United States alone. Professor Herr has given numerous lectures at international conferences and colloquia, including the IV World Congress of Biomechanics, the International Conference on Advanced Prosthetics, the National Assembly of Physical Medicine and Rehabilitation, the Highlands Forum XXII (Life Sciences, Complexity, and National Security), and the TEDMED International Conference. He is Associate Editor of the Journal of NeuroEngineering and Rehabilitation and has served as a reviewer for the Journal of Experimental Biology, the International Journal of Robotics Research, IEEE Transactions on Biomedical Engineering, and the Proceedings of the Royal Society: Biological Sciences.