

LESSON 11: MECHANICS MEETS BIOLOGY & MEDICINE

INTRODUCTION

BRUCE: When people think of biomedical engineering, biomechanics and biorobotics are likely among the first things that come to mind. Here, the application of engineering principles is very obvious. Still, the range of activities in this one area is beyond what we can hope to cover in this lesson. I'm deferring discussion of orthopedic implants to a lesson that includes biomaterials. That lesson also includes the influence of biomechanics on our understanding of the response of individual cells to mechanical stresses.

BIOMECHANICS

BRUCE: There really are two conceptually different but overlapping kinds of biomechanics: mechanical engineering used to augment biological performance, and concepts from mechanics used to model biological systems.

Some of the oldest assistive mechanical devices include the cane, the crutch and the wheelchair; however, today there are far more sophisticated mobility aids. Machines are helping stroke victims recover the ability to walk. And if you've seen quadriplegics self-propel their chairs and basketball players in the Paralympics, you know these aren't your grandmother's wheelchairs!

Cardiac engineering is also full of assistive biomechanical devices. Artificial hearts can keep patients alive while waiting for a heart transplant. And mechanical heart valves are available, as are stents that hold open arteries that might otherwise be blocked by plaques. These are all triumphs of both mechanics and materials.

If you look around a hospital, you'll see many other biomechanical devices—from infant incubators to heart lung and ventilation devices, to the ubiquitous infusion pump, which offers reliability and precision often taken for granted.

Biomechanical engineers have excelled at using their knowledge to model the motion of the body to understand everything from the performance of Olympic athletes and race horses to the gait of patients who have suffered strokes. The difference is that the mechanics of biological systems are typically far more complex than man-made mechanical systems and often require newer and more advanced analytical techniques, which, in turn, can be used for other engineering problems.

Designing for the Market

HOMAYOON KAZEROONI: What I'm working on, is to design these devices to be rather low cost and accessible for a large community of people in various applications. We're really thinking about consumer type devices rather than a capital equipment, so we bring it down, but the same level of performance and you probably have seen that stuff in other technologies, right? Mainframe computers

which are rather very expensive and high-performance, and you're talking about a desktop machines that does the same thing for people but more accessible and it gives them an ability.

Every stage I'll make sure engineers on my team are on it to make sure that we are not adding too much, because every time you add something in the device, one more sensors or one more hardware, and then someone has to pay for it. So we start from beginning. And more importantly, how do I make this thing light or minimal in every sense: volume, weight, price? The weight of exo is down to 13 kilograms, about 27 pounds, 26 pounds, in that which is almost half of the previous exoskeletons we built. The price is almost one-third. It really comes down to earlier stage of design, that what the requirements should be. So at the very early stage the designer, the people who actually put a lot of thought into this, they have to have their constraints in their head, we can't really come back to this later on, we start at the very beginning stage.

We have to really ask ourselves, what kind of maneuvers do they need? I don't wanna put too much technology in there to just make sure they climb the stairs. Just regular walking on flat ground, point A to point B, even if slow would be very enabling. So we bring our expectations down, we need to know what the patients need, and third one is we have to make sure we have the right engineering tools.

STEVEN SANCHEZ: Of course there's other exoskeletons out there. But the big problem with those is their price points: \$100,000—I can't afford. So what we're trying to do is get it to be on the affordable scale for everyone.

HOMAYOON KAZEROONI: I think this actually inspires the future engineers, the ones that is students right now, and others to actually think more and more and take on what we have right now, so after us they will actually bring that, even minimally in terms of volume, weight, cost, everything, to people.

BIROBOTICS

BRUCE: The area of biorobotics is developing very rapidly because of advances in mechanics and materials, but especially as a result of cheap and miniature computers for control. This is making possible new devices to serve biomedical needs.

There are multiple goals for Biorobots: some are designed to mimic biology—so-called “biologically-inspired” robots; others are designed to provide assistance to a human, such as the exoskeletons we just saw, and the advanced prosthetic limbs of an earlier lesson. We also saw assistive devices for rehabilitation that help speed recovery from an injury or stroke. Increasingly, biorobotics is also being presented in virtual environments to help train surgeons and dentists.

Perhaps the best way to learn about biorobotics is from one of the world leaders in the field, Paolo Dario of Scuola Superiore Sant'Anna in, Pisa, Italy.

A Pioneer of Biorobotics

PAOLO DARIO: My area of focus is biorobotics. When I started in the 80s to propose that robots could be used in medicine, we were considered as crazy people, very dangerous, almost killers, potential killers of humans using these strange machines. And I conceived to understand how humans work, because you can do, and many colleagues here do, modeling, just mathematics, simulation. But also developing physical model of humans or worms or crickets or birds or fish, is a very interesting tool. This

has been always the dream of humans, but now technology allows to do that in more realistic way. And I would say this idea, this was a dream 30 years ago. It's now becoming a reality, increasingly accepted. And so I'm proud of it.

Inspiring the Next Generation

PAOLO DARIO: I'm proud that I inspired many people, not only by teaching, but also by providing some hints maybe so the proposing crazy ideas or dreams so that then they make their own. Initially the idea was to develop an artificial heart, but the problem of the artificial heart, it was and still is power, you know? And so I moved to that and my dream was to develop a hand that could be like a bionic hand, with controlled by the brain directly and felt by the brain as a missing hand.

SILVESTRO MICERA: When I was a teenager there was a TV show called The Six Million Dollar Man, the story of an astronaut who became the first bionic man. And during the very beginning there was I guess the equivalent of the bioengineer or something, saying, "We can rebuild him, we have the technology." And I wanted to be the guy rebuilding people after these kind of problems.

PAOLO DARIO: Silvestro was my student, I started working with tactile sensor in 1982 and Silvestro started working around this pipeline in 1993, about 10 or 12 years later. And then of course he became really what I'm saying, I inspire people, I didn't do everything by myself at all. And now he's a recognized leader in that area. And a couple of years ago, with the contribution of many people, with a vision, and a determination too, we were able to plant such a hand in humans.

DENNIS: It was quite amazing because suddenly I could feel something that I haven't been feeling for nine years: soft.

SILVESTRO MICERA: For the first time, we were able to restore real-time sensory feeling, in an amputee, while he was controlling this sensorized hand.

PAOLO DARIO: It is possible, that through implanted miniature interfaces, it was possible to control the hand with thinking, by thought.

Bio Inspiration to Bio Application

PAOLO DARIO: I'm working in particular in the area of surgical robotics, or let's say endoluminal robotics, investigating, and then developing devices that can be used to explore the body, the inside of the body, using cameras, and doing things, doing actions, so cutting, suturing, and so on. My group is addressing a number of separate, individual issues. But the one in which I'm most interested is the gastrointestinal system. All of us should make endoscopic examinations. Most of those tumors if detected earlier can be cured 95% of cases. So it's really a life-saving procedure. But the traditional one is quite uncomfortable, and so reducing pain or discomfort is one of our main goals.

So the idea is to develop not only minimally invasive but painless system, for first of all for diagnosis. Our initial idea, of painless colonoscopy system, is based on the imitation of the worm. We took inspiration actually from worm locomotion, that is soft and flexible, based on pure or most pure science. Then we moved to engineering and then clinical applications. And finally, students of mine had created start-up companies that is manufacturing and selling this. It's one of very interesting case of a

full bio-inspiration that became a bio-application, it's the fulfillment if you will, the conclusion of a cycle that start from science, goes to engineering, and finally to application and market.

SURGICAL ROBOTICS

BRUCE: The endoscopic robot at the tip of Professor Dario's probe can remove a polyp during a colonoscopy. That's just one example of the power of Surgical Robotics.

Surgical Robots are being used to assist in actual surgeries, allowing for more precise and less invasive interventions. Mechatronic, handheld tools allow surgeons to manipulate their hands at the macro level while affecting similar responses from a mechanical device operating at the micro level. One day, this could even lead to "cellular surgery."

Key to surgical robotics is the sense of touch, or haptics. Many researchers are exploring how to enhance haptic perception and feedback to allow a surgeon to virtually palpate and squeeze tissue and sense how deep to make an incision.

Let's take a look at the work of another world leader, Dr. Guang-Zhong Yang of Imperial College London.

Moving Towards Precision Surgery

GUANG-ZHONG YANG: In surgery we are moving towards something called precision surgery. What does that mean is that you want to use small incision and get to the places that you want to get, minimizing access trauma and also perform the operation therefore that you can complete and that the patient go home quickly. And to do this, then you need those instruments going inside a patient and then making complex maneuvers, and this is where the challenges starts. And to address all those challenges, they bring all sorts of disciplines together: imaging, letting you be able to see; sensing, being able to bring you the sensation. And also robotics or what we call the mechatronics, linking mechanical engineering and electronic engineering to be able to provide or construct those instruments to allow you to perform those dexterous tasks.

What you want to do is to extend your hands and be able to do things that you cannot do with your bare hands. We know that for my hand for instance, that depends on what I did the night before that shakes a little and for many surgeons that inevitably that dexterity changes depending on how fatigued they are, and so by bringing robots then you'll be able to number one, is to scale the motion. I can't draw a very small circle perfectly, but I can do a big circle like this. Then why don't you scale the motion?

And second one, you can remove the tremor. If your hand moves, this intrinsic frequency can be filtered out. And the other one is that you'll be able to bring in imaging. So when the normal surgeon performs surgical operations you can only see what is being exposed. But if you link preoperative imaging together, then even before you make the first incision or first cut, you'll be able to see what's under this. So therefore, give you the vision, the dexterity, the precision, and all these things combined together, this is really where the future of surgery is moving towards.

APPLICATION: The da Vinci Surgical Robot

GUANG-ZHONG YANG: There are already a number of commercial systems that are available for clinical usage that they have made significant advances over the last 10, 20 years. And the one such system is

the da Vinci surgical robot. And they have done fantastic job to align the visual motor access for keyhole surgery, you no longer, using this rigid simple instruments and also you have been limited by what we call the fulcrum effect because that you're making the small incision then you have to pivoting around this point. And the other thing is that you are having too rigid instruments projected what you see onto a screen which typically is 2D, and therefore you are performing procedures like this.

Now, I have analogy for you. And try tonight to have you a Chinese meal, and by having one chop stick in one hand and try to eat but, not looking at your food, by projecting, take your camera to take a picture and project it onto the wall and try to eat like this. You'll never be able to do that. And this is really a recipe for disaster and for errors, right? So da Vinci robot brings two, what I regard to be the two major advances: one, have the stereo vision, align your motor with your access; therefore, you see what you're operating; and second one, they're bringing instruments with those wrists very, very dexterous.

And therefore you'll be able to do things otherwise you actually even with bare hands you cannot do. And this really has transformed the field because that allow you to access to areas that's very difficult to access, making those operations very difficult to use normal instruments, even with your bare hands. And you're really combining the human cognition, human decision-making, and the maneuver with the machine position. Of course it does motion scaling, tremor removal, all these things. And of course, this is all biomedical engineering, and it's a great example of engineering combined with design and combined with all the sub-disciplines in terms of imaging, mechatronics, and all those things making such advance and ultimately changing people's life.

“Disappearing Robots”

GUANG-ZHONG YANG: In medicine, we're all working towards early intervention, prevention, and try to intervene before irreversible damage has been caused. And the nature of those intervention in future you will very much towards minimally invasive intervention and also microscopic surgery. I see medical robotics is very much similar to digital computers in the late 70's and early 80's. During that time, we have witnessed the significant advances in mainframe computer, what the digital computer can do, and yet we still feel very proud having those room with these big machines and to be able to do things really clever.

But in early '80s, then you start to introduce workstations, desktop computers, and what kind of transformation this has been made. Now fast forward, now in your pocket. You have one or two of those machines with equal computation power to those machines in the big room. Do you really think about it when you use it for all the things you want to do? You don't. Because the machine here is to perform a task that naturally is a part of your daily life.

But I think for surgical robot when you make those robots so small and when you go to the operating theater, you don't actually get distracted by those big machines. You hold up a surgical instrument, it doesn't look that, different, but all the cleverness is really imbedded within. You will be able to perform imaging tissue characterization in situ. We're already developing those devices, and be able to dealing with motion and all these things I talked about early on. Therefore that you are seeing these “disappearing robots”, in quotes, and what you are seeing is here is making the robot to become pervasive, making the robot to be part of the daily life. It actually start to disappear into the fabric of the healthcare profession.

An Operating Room in the Body

PAOLO DARIO: The next challenge is to use robots to reduce further invasiveness; maybe at the end having no visible scar. So for example, introducing the surgical tools through the mouth or other opening. So essentially, is like transferring part of an operating room inside the body. And then the surgeon is tele-operating the device or usually has some sort of what is called Master device, which are interfaces like joysticks or of course, much more. And then there is the slave, as it is called, the robot, the remote one, that has to transfer the intentions of the surgeon into movements and actions, so that the doctor can navigate like, he, or she, would introduce, his or her hands within the body without any incision.

HOW THEY GOT HERE

Paolo Dario

PAOLO DARIO: I started with an interest to become an engineer in Ferrari Formula One, okay? And I really, because I was and I'm still very fond of racing, myself, I'm a motorcyclist, I like all this world. And I was also considering becoming a doctor or to pursue physics or engineering. So at the end, the passion for racing cars, engine, the motor and so on, drew me to become mechanical engineer. After three or four years I said, well, what's the outcome of that? What's the benefit for society, for people, and all that?

I've been working in biomedical engineering for more than 30 years and gradually I came to this area that I contributed to establish. I worked with many people, I inspired many people, now my group is about 200 people, including 90 PhD students. And what is interesting is that I am a biomedical engineer, fully convinced, but I'm also working in robotics and I'm working with and using physics, I'm working with and using medicine, and some former students of mine are working in Ferrari Formula One. So at the end, it's like connecting the dots, you know? I think the dots are well-connected.

EXERCISE

BRUCE: Before we meet again I have a quick assignment for you:

See if you can identify a friend or a family member who has used a biorobotic device, perhaps for rehabilitation, or as a surgeon. If you can't think of anyone, have you used a haptic device for game playing? It's not as big a step as you might think from a smart glove to a surgical robot.