

STATE-OF-THE-FIELD DISCUSSION

At the Crossroads: Interdisciplinary Paths to Soft Robots

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Participants: Randy H. Ewoldt,² Mirko Kovac,³ Hod Lipson,⁴ Nanshu Lu,⁵
Mohsen Shahinpoor,⁶ and Carmel Majidi⁷

AS I MENTIONED IN MY EDITORIAL, soft robotics is a highly collaborative field that relies on successful innovation in very diverse fields. Even the construction of a simple modest device might involve research spanning materials science, control theory, sensing, energy storage, flexible electronics, and a host of breakthroughs in more than one of these fields. Most researchers I know are fully engaged in the advancements within their own field and often lack the opportunity to discuss their projects and their project needs with experts in other disciplines. It is also a challenge for researchers with different backgrounds to communicate effectively and to be aware of new developments in distantly related technologies. A goal of *Soft Robotics* is to bridge such communication gaps and to share these collaborative discussions with you.

To those ends, I have asked each of the following experts to comment on the state of their particular field: Randy H. Ewoldt, Design of Rheologically Complex Materials; Hod Lipson, Evolutionary Robotics; Mirko Kovac, Biomimetic Robots; Mohsen Shahinpoor, Soft Actuators; Nanshu Lu, Flexible Electronics, and Carmel Majidi, Soft Robotics. These insightful perspectives will be followed up by a lively discussion among the participants.

—Barry Trimmer

I am happy to go first. I am Barry Trimmer. My primary appointment is in biology. I have an appointment in biomedical engineering and neuroscience at Tufts University, and I am Editor-in-Chief of Soft Robotics.

Mohsen Shahinpoor: This is Mohsen Shahinpoor, University of Maine, Department of Mechanical Engineering and Biomedical Engineering Laboratory, as well as the School of Biomedical Sciences and Engineering. I am a chaired professor and also the chair of the Medical Engineering Department and the director of the Biomedical Engineering Laboratory, and I am very happy to be part of this team.

Carmel Majidi: My name is Carmel Majidi. I am an assistant professor in the Department of Mechanical Engineering at Carnegie Mellon University. I also have a courtesy appointment in the robotics institute, and it is a pleasure joining you guys for this.

Mirko Kovac: My name is Mirko Kovac, and I am here at the Imperial College London, where I have an appointment at the Aeronautics Department, and I am a lecturer—actually, they call it lecturer here, which is basically the same as an assistant professor, and it is also my pleasure to join.

Nanshu Lu: Oh, hello everyone. I am Nanshu Lu from the University of Texas at Austin. My department is aerospace engineering and engineering mechanics, and I also have an affiliation with the Texas Materials Institute, and I am working on flexible and biointegrated electronics, mostly the mechanics and materials part.

Randy H. Ewoldt: This is Randy Ewoldt. I am at the University of Illinois at Urbana Champaign in the Department of Mechanical Science and Engineering. We throw the science in there because we like to give a tip of the hat to some of the more fundamental things that we do here.

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My research area is in soft, squishy materials, especially their physical properties. That is usually called rheology and trying to work with rheologically complex materials, trying to do something with squishy bits.

Hod Lipson: My name is Hod Lipson. I am an associate professor at Cornell University in Ithaca, New York. I am affiliated with the Mechanical and Aerospace Engineering Department.

Barry Trimmer: *I know that not all of us are actually roboticists as such. We come from very different backgrounds and different fields. Sometimes seeing how your own work fits directly into soft robotics can be an issue.*

What we are trying to do with the journal is to encourage folks from these disciplines that enable the technology for building soft robots to think of themselves as being affiliated with robotics. You know, I am a prime example of that because my main area is in neuroscience and locomotion in animals. So the journal is trying to draw on a wide range of disciplines. I think it is a challenge, but it is also an opportunity because we get to have a dialogue. We get to talk. We get to see one another's work and cross over.

I think where I would like to start, if it is okay, is with Mirko, who has been thinking about building robots, and ask him, "Which of the disciplines do you think is creating the biggest barrier to making effective soft robots?"

Mirko, do you want to try to kick off an answer? By the way, we might all end up focusing on one person here. I apologize if someone's field ends up being the main barrier to everyone else, but at least we will have identified it. So Mirko, would you like to start?

Mirko Kovac: I think soft robotics is a very young field, and it is very difficult actually to answer this question, because it could be potentially many different fields that have a tremendous impact on soft robotics.

Thinking about that—and my background is more on bioinspiration and building robots that are biologically inspired—I have found that actuators are very important. Standards are very important, and batteries are very important. These are the three main challenges. There might be more, but these are three of the main challenges, I would say.

Now if you want to improve these areas, then we have to think about chemistry and material science. I think that is a very obvious field that has a big impact on soft robots and what kind of soft materials can be used. What kind of living materials or polymers or liquid metals like EGain or different similar metals and materials. So I think that is one area.

However, instead of the development of new materials, we must look into how we can use the existing materials to improve efficiencies. Instead of having better batteries, we can improve the efficiency of our systems and then reach the same goal.

Now if you think about the efficiency and we take the example of flying robots, for example, we see that flying robots, or let us say flying animals in that case, greatly exploit the softness of their structure. So, for example, they use the flapping wings or the inherent dynamics during flapping of the soft materials of their wings to improve the fluid dynamics to improve the flight efficiency.

Now if we are able to identify what makes this interaction of fluid and structure very efficient, we are able to build better soft flying robots. So my main field that I would like to say here that can make a big impact is aeronautics or aerial robotics and traditional airplane structure engineering, which can actually exploit this structure/fluid interaction in a beneficial way for soft robots.

For flight, but also for swimming or for locomotion on ground where you always have fluids or soft structures in the environment, you can then apply these same principles.

Barry Trimmer: *Wonderful, you gave an example specifically in aeronautics. But you are talking really about the way we match the compliance and the mechanisms of the locomotory system to the environment. So whether it be in the air, in fluids, or terrestrial locomotion, the increase in efficiency is something that is going to be an enabling technology, if you will.*

Mirko Kovac: Exactly. It is really how to use the soft materials properly to actually improve efficiency. Now for flight or for like fluids, this is very, very important. It might be also very important for walking or running robots, but in flight you are bound to do that. So you have to really do that if you want to have animal-like locomotion capabilities.

Barry Trimmer: *Right. Okay, thanks. Carmel, can you add to that because I think you are thinking about similar issues—which of the disciplines do you see as a barrier? Is it overlapped with Mirko's sense of the limitations of actuators, sensors, batteries, and then compliance matching and efficiency?*

Carmel Majidi: Right. It is good that we have identified the similar challenges. In actuators and artificial muscles, there has just been a lot of incredible progress. I think that there are a lot of opportunities to create actuators not so much for reversible shape change, although that is also important so actuators can perform mechanical work, but also actuators that can tune their elastic rigidity, just like natural muscles. That is especially important when it comes to compliance-matching, human-machine compatibility.

Mirko mentioned batteries. Potentially energy harvesting also might be an emerging domain in this field. With sensors, I would kind of tie that into the broader need for artificial nervous tissue or artificial neural tissue that is capable of processing circuit-type functionalities sensing. Basically, we have to develop all the things that you need in your robot so that it can function without any kind of elastic rigidity.

Barry Trimmer: *Right. So very similar thoughts on that. If I can throw this toward Mohsen a little bit. It sounds like actuators are high on the list of people's plans. Within that also, of course, is the ability to actively change compliance or stiffness. So would you like to comment on that or give us some idea about the limitations in the field that you have worked in?*

Mohsen Shahinpoor: I am very much involved in basically soft robotic materials, such as electroactive polymers, and in particular ionic polymer methyl composites, or IPMCs, that I introduced in the early 90s. These are basically soft materials

that can be robotically controlled by electricity or by electrochemistry.

In that sense, it is basically rearranging the ions inside these materials, and because of that rearrangement within the material, you basically cause the material to deform in any way that you would like to. Thus, you begin to see soft robotic materials both in sensing and actuation as well as in energy-harvesting applications.

And I also come from a very strong robotics background. In fact, I was the first mechanical engineer to write a book on robotics many, many years ago. And so in that sense, you know, I have been fortunate to be able to integrate both of these because I come from a very diverse training background, initially in materials and chemical engineering and biomedical engineering, and then I got into mechanical and aerospace engineering through some strange twist of events.

But be that as it may, this is where I am now. You know, basically I feel that this is an extremely important field, and as was mentioned by Mirko and also Carmel, this field is truly exploding, especially in terms of biomedics and also the biologically inspired materials and systems and devices. This idea of back-to-nature engineering is truly a magnificent idea, and we are moving in that direction because we see how smart nature is, and there are so many things that we are discovering, not only in biomedical engineering, because you actually look at the different organs of the body, for example, the eye or ophthalmology. The more you learn about the eye, the more you realize how smart this rather analog system is and how it actually behaves digitally when it needs to.

Then, as Carmel also mentioned, you also talk about artificial neural tissues, the neurons, and how the axons grow and connect with other axons, as well as determining the fundamental laws of nature behind that. What are the forces behind that?

Of course, you know, there are a lot of mysteries in what we are doing too. There are so many things that we have not been able to answer. But be that as it may, I think this is a very exciting journal, and I am glad that we have initiated it.

Barry Trimmer: *It was a great honor to have you contribute. Can I put you on the spot with a specific question, though, about actuators? I think this comes up time and time again. You know, you make wonderful materials that are exciting because they are soft and they can move, essentially, and they can change the stiffness and everything else.*

The limitation, I think, many roboticists feel is in the interface. How do you connect this to a mechanism and to its control system? Do you see that as being a really important area or one that is relatively easy to solve?

Mohsen Shahinpoor: No, it is not relatively easy to solve. It is very difficult—interfacing is really difficult. Just to give you an example, a few years ago, I did work with many neurosurgeons and even heart surgeons and general surgeons. Even currently, I am doing work with bariatric surgeons and orthopedic surgeons and trying to introduce sensors and actuators into robotic surgery.

This interface is possible, but it is very difficult. At one time we were working on creating joint motion for fingers, and we were basically placing these bending actuators over the joint so that one end of it was connected to one of the bones in the finger and the other was connected to the other one, so that as

it moved, as it bent, it actually moved the joint, the finger at that joint.

However, the problem was that some friction between the actual strip was over the joint, connected to the bones. The connection to the bones was not a problem because we could use biocompatible adhesives or other types of binders to connect. But the problem was that as the strip moved, it also experienced extension and the reverse of that. In fact, it kind of hampered the movement a little bit.

And so we had to actually introduce seven kinds of accordion-like flexors to also accommodate that. The reason why I am belaboring this is that your question is very valid. Yeah, it is absolutely true that interfacing is absolutely necessary, but it is highly nontrivial.

Barry Trimmer: *I would like to turn the question to Nanshu a little bit because we have touched on the idea of control and of sensors and interfaces with soft materials, and obviously this is where you come in with the flexible electronics. Could you answer how we might make better sensors and actuators, but also see whether or not there are things in the other fields that limit the applications in which you would like to see your materials?*

Nanshu Lu: Sure. Thank you very much. Basically, from the electronics point of view, we have been focusing more like the sensing part rather than the control and actuation parts. For the sensing, actually, we have received really tissue-like electronic depth and have exactly matched mechanical compliance and thickness as tissue. We can perform multifunctional electrophysiological sensing, temperature sensing, hydration sensing, and also some radiofrequency ablation, some kind of treatment capabilities.

But the challenges we see, like in my field, are really in three major areas. The first is an interface, as I echo what most of you just mentioned. We are concerned more about the robust binding/adhesion between the artificial or synthetic materials and organisms, and also we are concerned about the biocompatibility, as well as an even biotransient or a bioresorbable material.

The second area with the underlying big challenges is the power supply, which also has been mentioned. I see the solution coming from low-profile lithium batteries and also some sort of energy-harvesting system to basically charge the battery. For example, with flexible kits or electric systems or even with those intrinsically soft materials like electrical, electro-active polymers, things like that.

The last area is about the data storage and transmission. Currently, there are not many integrated systems with all power, data, and sensor actuators integrated as a close group. And primarily that is because the power and the data are not quite ready yet—not as well developed as those on soft and biocompatible sensors.

Barry Trimmer: *Thank you. That is a very nice summary of the areas that I think would benefit your field a lot. I actually had not really given much thought to the idea of data storage in soft systems. That is a really interesting aspect.*

Can we turn and bring Randy into this equation a little bit because you are an expert on materials and soft materials. What do you see as being the main limits in other disciplines that prevent materials from getting into applications?

Randy H. Ewoldt: I thought about that question leading up to this roundtable. I feel like it is less of being inhibited by other disciplines and more that there is opportunity that people in my field need to figure out some barriers to be able to offer that opportunity to other fields.

I tend to think about materials that are very nonlinear in terms of their mechanical properties. These are things that reversibly go from solid to liquid based on lots of different things in their environment. This could be time scale. This could be how big the stress loading is. This could be electric fields, magnetic fields. Whatever it is, the properties vary by a huge degree, and there is some precedence for this being used a little bit in the world of robotics and other disciplines, but there is much more opportunity that I see that has not really been achieved yet.

Biology is, of course, is a huge inspiration for seeing these weird, nonlinear—dramatically nonlinear materials—in action. I think one of the biggest inhibiting factors is in terms of how complex it is just to keep track and describe these properties.

So most material properties are described by constants. You know, if I am talking about a soft elastomer, what is the modulus of the material? Or if I build a structure out of things, what is *the* compliance, as if it is a constant. That can get you a lot of mileage to be sure, but I think there is a lot more opportunity to acknowledge what I would call function-valued properties—so a modulus that changes depending on huge dimensional space. Like I said, time or stress-loading or other environmental factors.

We do not seem to have a very good way of keeping track of that. For example, there are no material selection charts for function-valued properties. You know, the classic Ashby diagrams I use when I want to choose something that is stiff, but the density is low. And Michael Ashby and others have organized these charts. They are just really beautiful for choosing those materials. But there is nothing that exists like that, that I know of, for these higher-dimensional mechanical properties, these function value things, materials that are viscoelastic. And biology is full of viscoelastic materials, not just because they have to be, but because they actually provide a lot of function.

I think that is probably one of the biggest barriers: just organizing even the material property database. And then beyond that, of course, it is a much richer question about what properties I want—and that is a big challenge in terms of modeling with mathematical models that involve function value properties. But even if I know what I want, then how do I get it? And how many different ways can I be creative about what I put inside of my elastomer or my colloidal polymer composite, whatever it might be, to get these peculiar properties that I am after.

Barry Trimmer: *Thank you. That is really fascinating. We probably should be taking that whole idea, that function value idea of materials and treating it not as a problem in engineering, which is what is typically done where we try to linearize the system and try and remove a lot of those issues, but to actually think of that complexity as part of the answer, that the complexity is something you exploit and you use to your advantage. It allows you to offload some of the central computation that might be a problem to the nice complex transfer function that the material gives you.*

You know, I think of purely elastic materials as very boring. It is a linear system. It does not do very much in terms of calculation. But something that has viscoelasticity has now got a time-dependent calculation happening constantly. If that was available in a database, that type of thing, I can see engineers exploiting it and not treating the material complexity as a problem, but as an answer, to their design problems.

I think that is a lovely idea and a lovely way to think about that. I do not know if anybody has got anything to add on those topics. I have another topic I wanted to raise briefly, but does anybody want to follow up on some of those ideas? Is there anything that has not been said in the area?

Mohsen Shahinpoor: We have talked about materials that go from liquid/solid—Randy mentioned that. Of course, there are many of those types of materials, such as the magnet or rheological fluids in a composite form with rubber elasticity and sponges and this, that, and the other. We have done some of that work for basically transcutaneously activating valves and pumps inside the human body from outside magnetically.

So yes, I think that is an area that we should definitely look into for this journal, and I am glad that Randy is into those areas. That is good that we are also addressing such face-changing soft robotic materials.

Randy H. Ewoldt: Mohsen, thanks for the vote of confidence here.

Barry Trimmer: *The other aspect that has come up a couple of times in addition to the sensors and actuators, which ultimately comes down to materials, was power. Mirko and Nanshu talked about being efficient or actually harvesting energy.*

We still end up with a problem that lithium iron polymer batteries and capacitors do not have the same energy as gasoline, for example. Do any of you have some radical suggestions about solving the power problem?

Mohsen Shahinpoor: Boston Dynamics has created the big dog and other types of humanoid robots using miniaturized internal combustion-type engines. To reach that kind of an energy density, fuel is one area to use miniaturized internal combustion engines. The other one is probably also fuel cells.

Barry Trimmer: *One of my more radical suggestions is that we exploit the same system that biology uses, which is energy-rich hydrocarbons, just the same as you would use gasoline. Fat, for example, is an amazing energy source. It has the same basic energy density as hydrocarbon fuels. But animals consume it indoors safely without massive heat production, without any dangerous emissions other than some carbon dioxide and water. Although we have to change completely the types of technology, and the actuators and materials that we use, if we could exploit the chemical energy of hydrocarbons in our robotics system, we would at least have something as equivalent to our current machines in terms of carrying its energy power supply with it. The other way, I guess, is to make things extraordinarily efficient so that we do not need to carry as much energy.*

Carmel Majidi: That is kind of an argument for biohybrid-type artificial muscles and machines in which we hybridize living tissue with these engineered materials. So we have tissues that are just powered off of sugars and fat.

Barry Trimmer: *I just wonder, Hod, if you could answer the question, what in the other disciplines do you see as a barrier to making soft robots and to moving forward in your field, and also perhaps my question that information and calculation in materials is really an important aspect.*

Hod Lipson: I think the number one barrier is soft actuation. We have been struggling with this in various ways. We can design all kinds of crazy soft robots, but at the end of the day, how to activate them is always a challenge. We end up having to put some form of hard activator or some complicated other kind of device in there for energy.

So energy and activation have always been, I think, the big practical challenge for us. But beyond that, to kind of broaden the discussion, I think there at least have been two big challenges and that is design and simulation of soft robots. Being able to simulate soft robots is very challenging for a computational system.

Recently, there have been a few of these soft mechanic simulators. They are much more difficult and complex compared to rigid body mechanics, where there is quite a lot of simulation tools out there. Soft material simulation is tricky, and it is particularly tricky if you want to have it match reality. In other words, we are at the point now where we can make soft simulations that look right in terms of their animation element and graphics, but they do not match reality.

Matching reality is very tricky because it has to do with capturing material properties—the viscosity and all of that. So I think that is a big challenge. If you want to design anything that is nontrivial, you have to be able to simulate it. That is kind of across all engineering and is certainly true for soft robots.

The other aspect, which is broader than simulation tools, is design tools. I think they go hand in hand. What I mean by design tools are basically design automation tools. In other words, we want to be able to say, “Here are my materials. Here is what I need the robot to do. Find a way to put these materials together, exploiting properties of soft materials in order to accomplish my goals.”

And it could start with something like design a soft robot that can crawl through this obstacle or could jump over that hurdle or can do this and that. In order to accomplish these—this design automation challenge, which again is something that in robotics we see more and more of both in automatic design of the control and automatic design of the body. In order to have that work, you need to have good simulation.

So this sort of builds upon the need for a simulator, but once we have a simulator, we need design automation tools. And I think often manufacturing design and simulation are sort of neglected because they are an afterthought to many of the robotic field challenges. But really they are key enablers that allow the whole field to move forward.

If we have a good simulator, for example, a good, automatic design tool, then we will be able to make much faster progress for the entire field. So I see these as barriers at the moment.

There is also manufacturing. With 3D printing and so forth, these tools are allowing us to make much more elaborate

shapes and freeform shapes, but they are not very good at making soft materials.

Again, much of the development in 3D printing, for example, is for hard materials. There is a little bit of elastomers, but again not the kind that can be actuated. So there is work to be done there as well.

Barry Trimmer: *Thank you. I think that it is fascinating that Randy, who works in the area of complex rheological materials, and yourself have sort of put your finger on a similar problem. That is, we need to know how the materials work, how they can be described, and catalogued and accessed. Beyond that, even if we knew that, we need to have a good way of capturing those properties in physics simulators.*

When you think about it, there is not a single machine these days that gets built before it is simulated. They do not guess whether or not an airplane is going to fly. They know it is going to fly. The simulations are very good. And we are nowhere near that. So we are still relying upon putting things together, see if it works and then get some intuition, rather than actually having good, physical simulations. I absolutely agree with you on the design side too because that feeds directly in.

Hod Lipson: In fact, I think that the challenge is bigger with soft robots than with traditional rigid body robots because, as designers, we have much less intuition about soft robots. There are just more degrees of freedom, and it is difficult to imagine and to intuit what could and what is going to happen. So we will rely more on these simulators than we do with the rigid body robots. And rigid robots are already difficult to design, and so with soft robots this will be an even bigger issue.

Barry Trimmer: *Right. I absolutely agree. In my own lab group, I like to give the example of a partially inflated long balloon. When you have the balloon and the little part—the little nipple at the end is not fully inflated, that part is very soft and the rest of the balloon feels very stiff. But the pressure inside is identical everywhere. And yet your intuition, because of the difference in tension in the wall of the balloon, is that there are different pressures.*

It is very hard to even imagine exactly what is going on, and you need to be able to do the math. If we have not got good descriptions of the materials and the properties, we are not going to be able to do that.

I certainly think we have got a whole lot of interesting areas that we have managed to touch upon. Does anybody have anything they would like to add? Also if you have any idea about what the killer application is going to be for soft robots—if anyone could just comment on that briefly, and I think we can then wrap it up.

Mirko Kovac: I have a comment on the design question. So as Hod had mentioned, I completely agree that having good simulations might actually really improve the field, and also having revolutionary algorithms, as Hod is working on, so that actually the designers and the robots design themselves in some way.

Now on the work that I was doing before, like small jumping robots and small bio-inspired robots, we simulate them as well. We do calculations with neat elements and all different things. But once we try to build it, it always ends up

quite different than you actually expected it to be from the start. So if you have small structures, a small difference in fabrication makes a big difference for the behavior of the materials and the whole mechanisms.

Now if you look in soft materials, as we mentioned before, we really want to integrate material properties with fabrication methods with actuation sensing and interface and all that. So basically we want to create a system that has all this integrated together in a smart way. That is really a very, very complex multiparameter design process that is not only on the material properties but also on the fabrication and also on the interfacing. So we have to keep in mind that prototyping and actually the design or the human that is there building the robot does make a big a difference, especially for the fabrication and interfacing of the electronics, for example.

And so I think what is really important is to think about design frameworks, one of them being bioinspired designs. So how do we actually come up with ways to integrate all this and do this in a creative, out-of-the-box manner?

To do this through prototyping and through the humans that actually build them so that we come up with novel solutions and novel robots in a very smart way, we have to keep the design process prototyping and clever creativity methods in the loop when we build robots.

Carmel Majidi: With regards to the killer applications, to me I guess the thing that intuitively stands out would be personal robotics and kind of wearable robots more consumer or personal use. I think the unique advantage of kind of soft machines, soft robots, is the fact that they are naturally somewhat compatible. They achieve that natural compliance matching with human tissue, so they are safe. They are comfortable. They are wearable. So I kind of see that as a very exciting domain and market.

The other one is 3D printing, and I see that also as a growing market—it very tightly complements the emergence of soft robots. I see them basically as personal printers, where a hobbyist or any kind of nonspecialist could print out their own custom soft machine or soft robot.

Carmel Majidi: For the research we do, 3D printing is a big part of how we build these robots. Not just in terms of a commercial fabrication tool but an area of open research. So I do see soft robotics and 3D printing as being very closely aligned.

Barry Trimmer: *I think I see 3D printing as a tool that is going to develop. It is going to develop in lots of directions, with better materials and more ways of making soft materials shapeable. But I do not think it is a core area as such. I think it is a tool for people like ourselves to use and to access and keep our eye on, but the technology developing the 3D printer is not necessarily all about the same concepts that we are discussing.*

Mohsen Shahinpoor: And actually, we should all remember that really 3D printing is an extension of rapid prototyping. These technologies have been around: serial lithography, selected laser centering, fused-position modeling, and basically how you put STL files into your printer and put one layer upon the other and how you embed the structures into those layers by various means, either by cueing or by centering or by the new Z printer—the technology that

came out of the Massachusetts Institute of technology—one of our colleagues, Emmanuel Sachs, developed that.

It is kind of like laser centering, where you lay layers of powders and center them, but in this case Eli Sachs came up with a much smarter idea to use an ink jet printer cartridge and use a binder rather than ink, to shoot droplets at different layers and then create three-dimensional structures for printing in that sense.

So in that particular technology, the Z printer that Eli Sachs developed is commercially available, and in fact, we have one of those systems in our department. I bought it last year for \$64,000. And that allows you to create soft structures because you can use any kind of a powder. You can use metallic powders. You can use plastic powders. You can use soft powders, and you can even use binders that are basically elastic or viscoelastic.

So, now having said that, I want to go back to respond to Barry's question about soDme killer applications.

I think killer applications, in my opinion, are going to be mostly in health engineering, in biomedical engineering. As an example, I have done a lot of work in helping prevent heart failure, congestive heart problems, trying to develop soft, artificial muscle-type activators to enhance the pumping, to enhance the left ventricular myocardium to pump the blood, and to help congestive, weak hearts. And in that sense, the reason why this is a killer application is that, as you all know, heart problems are the number one killer of humanity...in the United States alone it is the number one killer.

In fact, every year over 1 million Americans die because of heart failure, and there are statistically currently some 85 million Americans suffering from heart problems. Somehow, none of the artificial hearts have worked because the body reacts to these machines as a big virus, or something like that. I am hoping that in the future I will submit an article to *Soft Robotics* on that.

But be that as it may, another killer application, in my opinion, is to get into biomimetics or biologically inspired systems. For example, we all know that birds, or even at one time dinosaurs, even flew because they had soft, flexible actuators as wings. And in fact, the birds undulate their wings to bend like an inverted U shape as you move up, but then they extend out and flap back straight down. They create a net lift. This is one of the dreams of humanity—to be able to fly or to be able to create artificial wings.

Hod Lipson: Maybe I can say a few words on killer apps. I presume we are talking about commercial killer apps. I think it will probably be just like many other killer apps, and that is gaming and entertainment. I think making toys and games is going to be the killer app for soft robotics, especially when you involve robots and kids.

Mohsen Shahinpoor: It is true that we can get into dolls and toys and all that. For example, consider an eyelid, which basically moves up and down because of the paraverbal actuators in the eye. That is not just a good application for toys, but it is also a good application for biomedical engineering because there are very many people who suffer from eyelid paralysis, Bell's palsy, and diseases like that. So there is a duality. There is a duality in these applications.

Barry Trimmer: *I would like to ask Nanshu a little bit about what she sees as a killer application coming from the area of flexible electronics.*

Nanshu Lu: Yes, thanks. To me, I am interested in the human integrated robotics. For example, prosthetic limbs, where we can have a close look at sensing, processing, decision-making and controls. So as I mentioned before, we are now very good at sensing, and examples would include a lot of research in artificial skin where tactile sensors as sensitive as human skin have been created, and they are as soft and flexible as human skin as well.

And we also have electronic eye cameras which have integrated compound eyes for the environmental imaging. And then in terms of the human machine and this integration, we have things like epidermal electronics. We have brain or heart-integrated electronics, which could perform a lot of sensing from human insight to really control the robotics.

And then another very important robotic application with human interaction would be surgical robotics. There, basically we also need *in vivo* sensors which could compatibly integrate with a brain, heart, epicardial, or endocardial. Minimally invasive balloon catheters have been created and they can perform really high-precision sensing and robotic surgery treatment.

But now as I have mentioned in the previous discussion, the actuation part is still largely missing, and I see that as a new field to look into... Yes, prosthetic limbs and surgical robotics.

Barry Trimmer: *Thank you. Randy or Mirko, do you have anything further you would like to add?*

Randy H. Ewoldt: I would say that I tend to think in the biomedical realm of matched compliance and things. But I think Hod is probably right. When it comes to commercial success, there is probably a very serious avenue to consider in terms of gaming and entertainment, in terms of the killer app and things really taking off. Those were two things that were said, but some comments on that.

Mirko Kovac: I have two killer apps that could be relevant in the future. One would be a human-machine interface in

which people are often afraid of robots or big humanoids. So if they are soft in some way, or mushy, they wouldn't be so scary or so hard. This might actually benefit the robotics field, because they would be much more human friendly. So human-machine interface on soft materials and skinlike structures can be very beneficial.

The second one is morphing wings or shape-changing structures. Let us say, like an airplane. British Airways systems, for example, have these morphing wing aircraft that have skinlike wings that can then change shape, and when they land, they have a different shape than when they are in flight, or... or Airbus, I think, has a study on that as well. If you have an airplane that folds up its wings with soft, skinlike material that fits into smaller airports, because in the future big airplanes will be much bigger, so they cannot use the airports that are built today, for example.

Also BMW has a study in which they use a car that has a skin, and it changes its internal structure so the skin performs like a living machine. It can change its aerodynamics as it is needed. So not just with a spoiler or a fix, but the whole car is a moving, soft, living, and artificial system.

I think soft robotics in the wider sense will merge much more with consumer products like cars, airplanes, or anything—like mobile phones might be soft as well at some point.

Barry Trimmer: *You mentioned gaming, entertainment, and human interaction. I think that is where we end up. On that note, I think it is probably an excellent place to bring things to a close. I really appreciate all of your comments here. We have a lot of interesting thoughts. Thank you for your candid, expert contributions to Soft Robotics.*

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