Actuation is a difficult affair in soft robotics

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Introduction

Imagine the world a hundred years into the future. You are walking down the streets of a busy metropolis. It's a nice sunny day, the sound of the city fills the air around you as you move along with your day to day errands. You turn the corner of one of the streets and bump into someone, or rather, something*. Something soft and squishy in fact. The figure in front of you stands some six feet tall, round and bulbous in its shape. Its arms are flexible, like the limbs of an octopus. It says, "I am sorry human, please proceed." And you realize, oh, it's just another robot roaming the city. You wave it goodbye and it does the same to you. Yes, what we have here is a glance at the future of robotics, namely, soft robotics!*

So what is soft robotics? Good question. But first, what even are robots? What components are necessary before we can call something a robot? Perhaps you have seen robotic arms in factories assembling cars or laser-cutting materials with pinpoint precision. Those are definitely robots. Even drones that hobbyists fly in the air count as robots. So I guess one way of describing robots is a machine capable of moving, of sensing things in the environment, and reacting accordingly. But you probably already knew that. So what makes soft robotics special?

The name should give you a clue. It is about robots composed of soft materials. Okay, so like adding padding to a grabber? Well, not quite. Adding foam around a robot does not classify it as a soft robot; it will still move with the same motion it always has and will not conform or deform any more than it previously did. Soft robots have limbs composed entirely of soft materials. That means that they are not limited by the stiffness and rigidity of metals or hard plastics. They do not have joints that enable rotation or linear extension of connected components. It is the material itself that flexes and extends to allow motion; just one homogeneous part twisting in whatever way at whatever point within itself. But why do we even need them?

Applications and relevance

The first answer is that it is very cool, and maybe it is enough of a reason to devote your entire life to this field. Thankfully, there are plenty of practical reasons as well. For example, surgery is one field that can benefit from soft robotics. You do not want something hard and rigid poking around inside you when surgical operations are performed. Soft robots have the possibility of moving around and accessing areas within your body that would otherwise be too difficult.

Medical sector

Minimally invasive surgery (MIS) as it is called in the medical sector is probably the most relevant application [1]. You avoid open surgery whenever you can because it is unpleasant and risks damaging other parts of the body. MIS involves using existing orifices that we have, or in the worst of cases, small incisions.

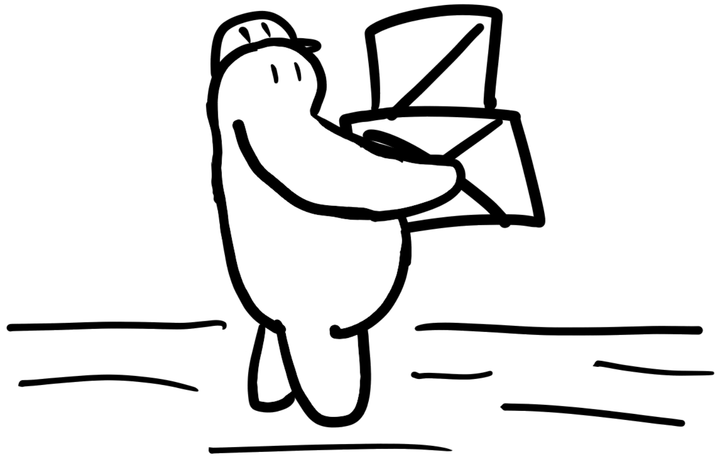
The imagery is not pleasant, but MIS makes use of long, flexible tubes with some sort of instrument at the end of it to reach the point of interest within the body. But there is not much point if you cannot control it. Conventional robots can be controlled, but they are most likely going to wreak havoc inside your body. I think you can see why soft robotics would be really useful here.

Cobots

But here is the thing. A conventional robot does not even need to be inside your body to potentially cause damage. There is real danger in having robots and humans working in the same space.

We can take a little peek at one paper for this. The paper described here [2] discusses some of the elements needed for cobots to be viable. It goes into lengths about different ways of optimizing the tasks between humans and robots, but more importantly for our case are the discussions about safety. All of these risks have to be documented. And how do we limit these accidents? One idea here is to designate areas where humans and robots have no contact, and add a middle section where interaction is possible. The thing is, there are certain tasks and decision making skills that robots just cannot replicate (for now). If such a situation occurs and happens to land on the robots-only zone, well then, good luck to whoever has to go over there and fix it.

I guess you could just turn everything off for a moment as well, but it’s better to make things efficient. It would be much easier if this middle section’s scope was bigger. And that is why soft robots could be really helpful in that regard. We reduce the risks of getting concussions just from standing right next to a robot.



Search and rescue

Another application for soft robots are search and rescue missions. Conventional robots are actually quite good at these things already. Robots for such missions have been put in operation since 2005 [3], and probably earlier than that as well. This paper in particular talks about the many use-cases of rescue robots. Japan is quite prone to natural disasters, and naturally we want to mitigate the damages to people and property alike.

Another paper from 2009 by [4] explores rescue and recovery with robots. This one is probably more relevant for soft robots because of the physical challenges that can be encountered by a conventional robot. You never know when a stray rock might fall and hit the robot, or perhaps its limb gets stuck. Being able to adjust its shape around obstacles would make it much easier for it to free itself.

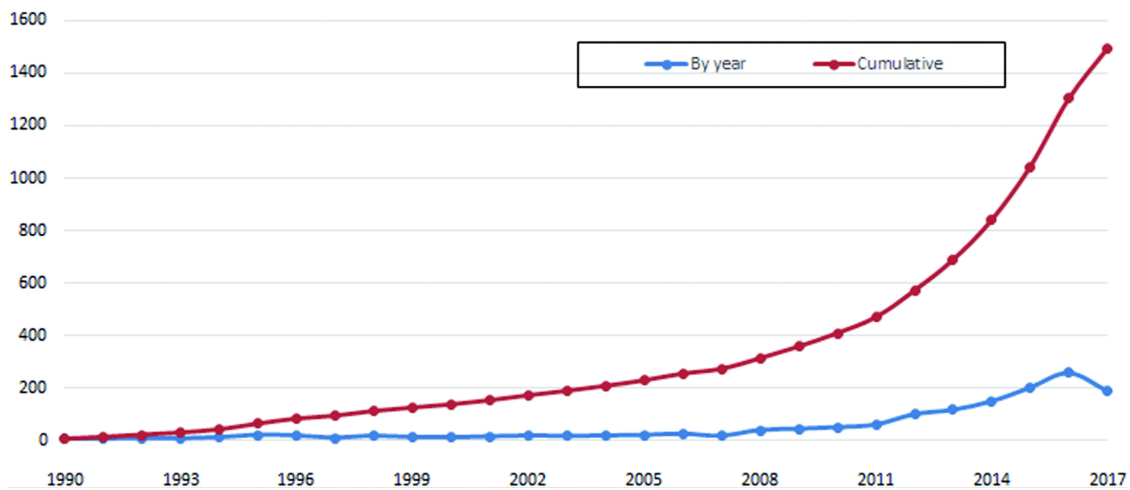
One takeaway for these search-and-rescue robots that have not been discussed much is the recovery and, for the lack of a better term, handling of the humans. This goes back to the point about cobots and how being hit by a hard conventional robot can be very painful. It would be best to handle injured people with utmost care. Cold hard steel or plastic are not the first things that come to mind for this situation.

And more!

We can go on and on about the applications of soft robots in all kinds of fields, but let's wrap it up and agree that they have valuable uses, and that is why further development should be done in this field. But I like to be extra sure, so let me point you towards some nice fancy statistics which show that, indeed, soft robotics *is* something that people are interested in (even NASA [5]).

Some statistics about soft robotics

For this we will have a look at a meta-analysis by [6] from 2018. It is a few years old, but still has some really good insights about the field. Papers related to soft robotics have increased exponentially over the last few years, as can be seen from the timeline from 1990 to the first five months of 2017. This trend is still on the rise as well. Here is a figure from the same paper.



In terms of publications per country, the United States is currently leading with a significant margin at almost 480 publications. China, which is second in rank, has roughly half the publications of the United States. There is plenty more information from their analysis about soft robotics, and I highly recommend you check it out. They have plenty of informatics and do not simply contain massive walls of text.

The problem at hand

But now I am sure at this point that you are, in fact, utterly convinced, and that now you are thinking, “You are right! That is all very cool and very useful indeed, but why have I never seen any soft robots?” Oh boy let me tell you, there are plenty of reasons! For now, we will only focus on one big problem. So big in fact that we have to visit all other aspects of soft robotics that make it the way it is.

Soft robots are hard to control. How in the world are you supposed to control something that can flop around in whatever way it wants? Its flexibility is also its downfall. We will learn here where the field stands and how researchers have addressed it so far. But don’t you worry, for we will embark upon this journey together. In fact, you, yes YOU, dear reader, will be at the helm of it!

Imagine this. You have unknowingly been super interested in soft robotics for like the past 10 years. This is a highly interdisciplinary field, and you know this as well. You have talked to your friends and colleagues about it. They think you are losing your mind, and some think you are just describing some outlandish concept. But among the naysayers, you have finally found a team that is willing to join you. Some of them are chemists, others are biologists. You have a mechanical engineer, an electronics engineer, a software engineer, you name it. Even that one guy you only ever say hi to in the morning. You don't know why he is here or what he can even do. But you do know one thing: he makes damn good coffee. In fact, he is everyone's favorite team member already.

You all sit down for your first real meeting. Now then, where do we begin?

Materials

To start it all off, we need to discuss materials. What do we choose for our materials? What properties do we need for our robot? Well this is actually a very difficult question. You may not like the answer: *It depends.* Remember, the heart of soft robotics lies within the material of choice. Where are you using this robot? What tasks must it accomplish? All great questions. The one thing we do know is that they have to be soft, but we will need some more meaningful terms that can describe them better.

What properties do we need?

For this, we shall look at some papers for inspiration [7]–[9]. Looking at these papers, we can form a list of what is most commonly looked at.

- Viscoelasticity
- Young's modulus/elastic modulus
- Fracture toughness
- Work energy density

Viscoelasticity

First up we have viscoelasticity. This is a term that can be split into two, **viscosity** and **elasticity**. Viscous materials are what can be described as being thick and melts into itself if left alone. Elastic materials should be quite familiar, these are materials that "spring" and bounce. Rubber is a fantastic example of a viscoelastic material.

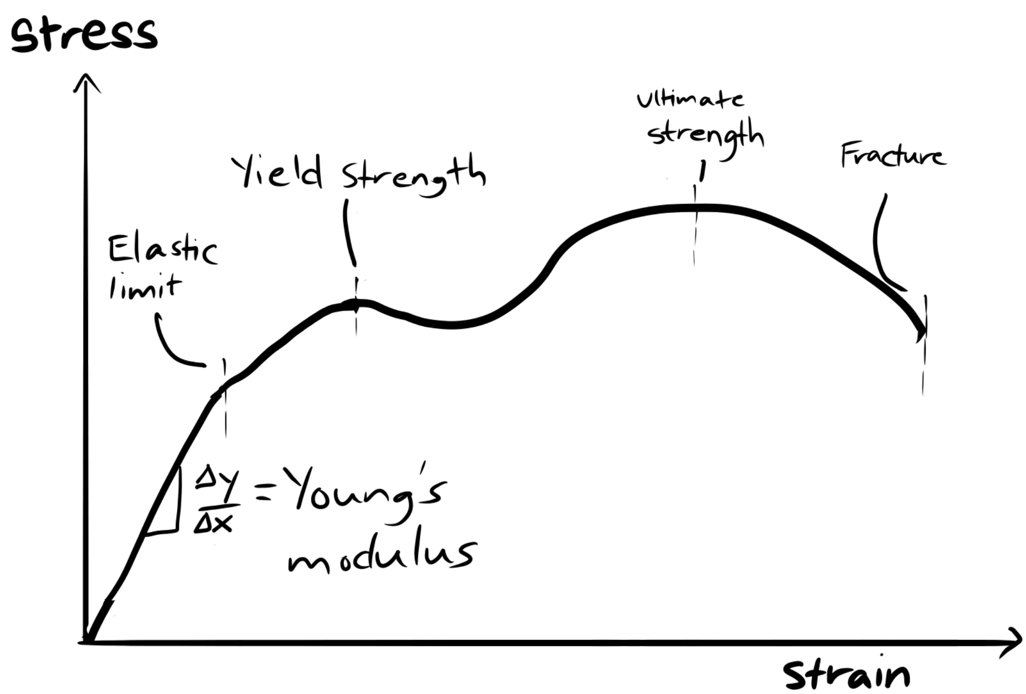
A material with high viscoelasticity means that it is also highly **compliant**, which is another term for describing elasticity, more specifically the amount of deformation for a given force. High compliance means that a load can be distributed more evenly over the material, which reduces the overall force experienced on any single point on the body. Think of it like the difference between pushing a pencil against a concrete wall versus pushing an eraser instead.

Viscoelasticity is one of the most important factors to consider when choosing a material . In a sense it encapsulates all that you're looking for in a soft robot. Still, it is helpful to have a few more properties to help select a material.

Young's modulus / elastic modulus

This one is also really important, probably only second to viscoelasticity [9]. In simple terms, the Young's modulus is a metric that describes how stiff the material is. When you apply **stress** (force) to a material, that material will stretch. The amount of stretch the material experiences is known as its **strain**. If you increase the amount of stress, the material will eventually get damaged to the point where it will no longer retain its original shape, even if you remove the stress applied. This means that the material has deformed.

Knowing the material's Young's modulus tells you how much stress it can sustain before suffering permanent damage. Speaking of permanent deformation, the point at which the material suffers this is known as the **ultimate strain** of the material. It is perhaps best to provide an illustration on how these are all related to each other with a **stress strain curve**.



Fracture toughness

Fracture toughness tells us how resistant our material is to fractures or cracks when damage already exists. These damages can exist as holes or deformations on the material, perhaps from too much stress being applied or simply a fault in manufacturing. This is extremely important for a soft robot. A tear on the material would basically mean replacing that entire piece, which could mean replacing the entire robot.

Work energy density

Last but not least, we have work energy density. This tells us how much work (in physics terms) our robot can do based on how much material we have. Despite the fancy term for it, this one is actually quite self explanatory. You want to avoid making a robot the size of a house if all it will carry is your laundry. Basically, it is the efficiency of the soft robot relative to its size.

Other properties

There are many other properties that need to be taken into consideration as well. The thing is, the previously mentioned properties have a higher priority for selecting the material. These other properties come into play when you need to get specific results from your robot. We have aspects like flexural strength, compressive and tensile strength and dynamic moduli and all kinds of other materials science terms [10]. All of which are useful, but we don't need them for now.

Putting it all together

I think we can agree that these properties are quite simple and self explanatory. The point of knowing these is to have some quantitative terms that we can use to describe our materials.

List of materials

This is good. Now we know more about what to look for. We can start looking at actual materials. Now, it has got to be said that plenty of different materials have been explored as potential candidates. This is not exclusive to soft robots but to robots in general that could benefit from using softer materials. And let me tell you, some of them seem completely out of line. I am not saying this to criticize the research that has gone into this. Rather, I find it very intriguing to see the extent of research done to find the most suited materials for this field. We have fancy scientific ones such as nanoparticulated polymer composites filled with carbon fibers and glass fibers. And then we have the ones such as corn starch. In case you are confused on whether you read that wrong, let me quote it the way it was written, "*edible-quality corn starch*".

I guess the point that I am trying to make is, there are a lot, and I do mean *a lot*, of different materials that have been tested and are still being developed. What we will discuss here instead are the ones that have garnered the most attention, and have been used within soft robotics to at least some degree. Without further ado, here is a list of these materials in no particular order [7], [8], [10]–[12].

- Shape memory alloys
- Thermoplastics
- Hydrogels
- Elastomers

Shape memory alloys (SMAs)

This is perhaps a strange one at first glance. These are alloys, in other words, metals. When you think about it, the only time metals are flexible is when they are in liquid form. Certainly, elastic is not the first word you would use to describe them. Well, these are specialized metals and alloys that bend and flex and allow motion using the laws of thermodynamics. When you apply heat to them, they bend and flex a certain way. If you remove the heat, they will slowly revert to their previous form (unless excessive heat is used). The fact that they are able to revert to a known state is what makes them suitable as a material. And as for flexibility, that will be taken care of when we discuss the structures that they take. Just as a little heads-up, they definitely cannot be thick and stocky in their form.

Thermoplastics

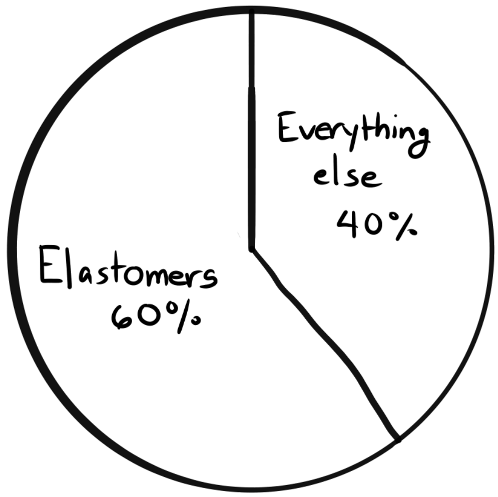
Thermoplastics are similar to the SMAs we talked about previously. The proper term for these would actually be **shape memory polymers (SMPs)** [13]. These are the polymer equivalent of the SMAs earlier. These are a bit more experimental in nature, but exhibit the physical properties of polymers while having the thermal actuation capabilities of SMAs. It is hard to say much more about these things when we are only describing materials. The differences between these will become much more obvious when we go on to discuss actuation.

Hydrogels

If you have never seen an image of a hydrogel, you should check it out. I have no idea why, but they just look so incredibly edible. Well, theoretically, these things are biocompatible and have even been used as a medium for drug delivery [14]. But we are discussing its uses within soft robotics, so how does it hold up here? They suck. They cannot be stretched much and are really brittle. However, scientists have devoted a lot of research into this and have managed to create hydrogels that go against this norm completely. These ones are highly stretchable, able to stretch itself several times greater than its original length, and are considerably tougher [15]. They are still kind of in an experimental phase though, often labelled as “future” materials within soft robotics due to its potentials. For now, it is just something to have in the back of the mind.

A word about what we have discussed so far

Here is a little secret. It may seem like a lot can be said about the materials mentioned so far. But in the realm of soft robotics, they receive far less attention than they deserve. Most of the time, the papers talk about elastomers. Here is a little image on what it's like looking at different materials for soft robotics:



Elastomers, the one and only

Elastomers exhibit most of the properties that we are looking for, especially when it comes to viscoelasticity. The only other material that comes close are hydrogels. They can be altered to fit more specific needs of a system. More importantly, they are safe to interact with. Some of the other materials may sound cooler, but the processes needed to make them move are not the most practical. Elastomers are also very cheap and readily available, and are super easy to manufacture [9].

A little bit about reinforcements

It is relatively straightforward in concept to reinforce something. We can think of this as adding a skeleton to the material, which can be done either internally or externally. This mostly depends on the manufacturing process for the robot. Sometimes it is simply easier to add it after manufacturing.

One thing to remember is that we are still trying to develop a soft robot. The reinforcements need to still be flexible enough as not to limit the entire motion of the body. Reinforcements are therefore used sparingly, often only adding stiffness in specific directions where there wasn't much movement to begin with. Oh and I almost forgot to mention, reinforcements can be made out of any material really, as long as it does not impede movement in the wrong places. The difficult part is making sure that it sticks to the main material, so glue tends to be used for this [16].

More to come

There are other materials as well outside of the ones discussed here that are only shown when we get to the topic of actuation. These are really difficult to talk about without going directly into the details of how they actuate and have therefore been left out of this discussion.

With that in mind, we can move on to how the materials we *have* discussed so far tend to be structured. This is quite important and will give some more insight on how they are relevant to the actuation part.

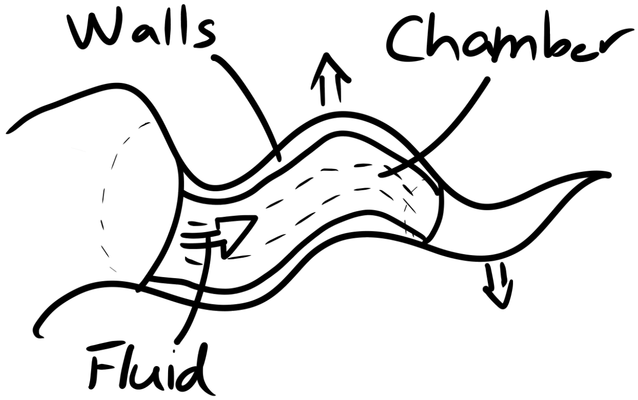
Months have passed since you all started working. Days upon days sitting in the lab, testing various materials, trying to figure out if they are well suited. One corner of the room has been filled to the brim with plastics and rubbers. The other corner, a bunch of shape memory alloys and strange hydrogels. Some of the material experts have brought different metals and glass composites. They swear they are flexible… just not right now. Cole the coffee man even proposed edible corn starch. But one material was present more than any other: elastomers. You almost feel sick staring at all of it. Functionally speaking, it is the most practical. It's cheap, it's easy to manufacture, most of all it flexes and bends really really well. But, it's just not as cool as the other materials. It may not be optimal, but you have to know what each one of these materials is capable of. Begrudgingly, you let your team know that you must use all of them.
"All of them?"
"Yes."
And with that final word, they nod their head in agreement. Some sigh in relief as they have come to appreciate the various properties of their chosen material. Others muffle words of frustration, "why couldn't we have stuck to one material?" Perhaps you have made an error in your judgement. But the choice has been made, and you must follow it and see it through until the end.

Structure and shape

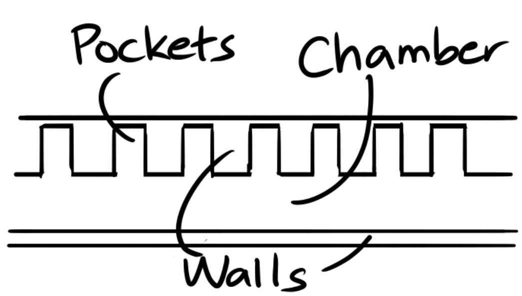
Shape is everything. I guess you could say the same about material selection, but this is even more important. The shape of our material ultimately decides what kind of movements our robot can do and how easily it can perform them. Now' let's look at some of these structures.

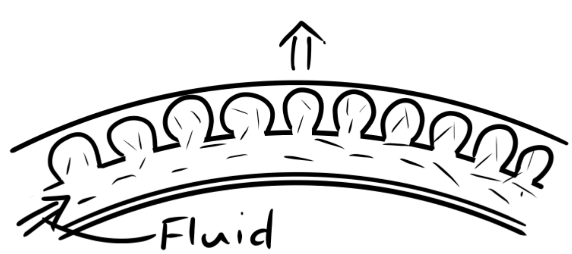
Typical elastomer structures

Some of the concepts for elastomer structures can be applied to the other materials as well. Speaking of which, there are a few ways to control elastomers, but we will only discuss the most commonly employed method, which is by using fluids [16]. The material is shaped such that the interior is hollow, which allows the fluid to apply pressure against the walls of the body. And that is pretty much the core concept of actuating these robots. From now on, we will refer to these hollow structures as chambers. Depending on how thick and thin the different points of the body are, the chamber may be enough to control the body.



However, we can take this a step further. We can get more fine-tuned movements by introducing pockets along the walls of the material. These pockets are connected to the chamber to allow fluids to also enter them. When these pockets expand, they apply pressure against the walls of the body, which amplify the motion of the body more so than only using a singular chamber.





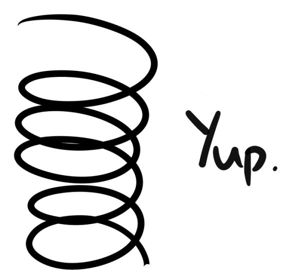
The body can be altered in many more ways, such as by adding bellows and pleats. Altering the structure of the body in this way is referred to as **mechanical programming**. You would be surprised to see the types of movements that can be achieved through careful alterations of the structure.

These are the core concepts used for building the structure of elastomeric materials. This is applicable to other materials of course. Hydrogels can make use of these structural concepts as well. The important thing is that the material is flexible enough so that the fluid can affect it.

You might already have looked at this and realized that we managed to actuate the robot, and you would be correct. However, there is more to actuation than this, and we will discuss it more later on.

Typical SMA and SMP structures

Remember when we mentioned that SMAs are not flexible? Well, by forming them into a specific structure, they become totally flexible. Actually there aren't a lot of studies that talk about the geometry of this actuator. The only real design is the spring coil [17], in which the only variation is the wire diameter, rod diameter, pitch angle, and number of active coils. The thing is though, this design works extremely well, so there hasn't been much reason to change it. The efficient design of the spring allows SMAs to expand many times its own length. Remember that SMPs basically function in the same way as SMAs. As such, they make use of the same structural design.



And there you go. Perhaps this was a little anticlimactic, but sadly it makes sense. You cannot deny that springs are flexible. The only other way of designing them is shaping them like a rod. Hopefully you will find it more interesting when we discuss the actual actuation methods of these materials.

Are there other structures?

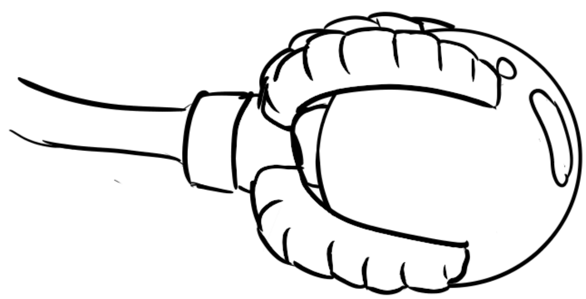
The short answer is yes. The long answer is, they are often niche or variations of the ones discussed here. Depending on how the actuation method is applied, it is totally possible to alter the structure into something more befitting of the movement. If that ever happens during the discussion, it will be pointed out. But now, it is time to move on to the main topic: actuation.

Actuation

And at last, we finally arrive at the topic of actuation. Where do we even begin? Well, we can start off by classifying the types of actuation methods that are used within soft robotics. As always, there are some niche applications that do not fall into any category. We will have to ignore those for this one. The ones listed here already cover a lot of ground. These methods differ based on the materials they require. Actually, it is more appropriate to say that the materials have been chosen *based* on the actuation methods we are about to discuss. Without further ado, here are some of the possible choices:

- Fluidic elastomeric actuators
- Shape memory alloys
- Electroactive polymers
- Variable stiffness

Fluidic elastomeric actuators (FEAs)



Fluidic elastomeric actuators probably make up most of the bulk of research within soft robotic actuation. Seriously. The list goes on and on [18]–[20][18]–[20][18]–[20]. Subcategories of this field include pneumatic and hydraulic actuation. It also goes by other names such as flexible fluid actuators (FFAs), but they all mean pretty much the same thing. So what is the operating principle behind this? Well, this type of actuation is pressure-driven. You have a material component that you can fill up with some type of fluid, and this causes the pressure to rise. The material component then stretches and expands in a certain direction. By altering the internal geometry of the material component, it can be forced to only bend or stretch in a certain direction. There are times when the design of the FEA limits the motion to only go one direction, and struggles to go back the opposite way. The solution to this is simple: you add more FEAs, specifically in the opposite direction to have opposing movements.

Based on that description, we can easily see what type of material we are talking about here: elastomers. I mean, it's even in the name. That does not mean that you are limited to elastomers though. Hydrogels and braided fabrics can also be used as the materials for it, it just so happens that elastomers are the best choice due to the ease of manufacturing the desired internal geometry.

This type of actuation is extremely simple to operate. You can pretty much think of it as a binary on/off control. You want to move your object? Alright, open the valve and fill up the chambers. This is obviously much easier said than done, mind you. After all, the valves also need to be soft [21]. However, the concept still remains easy to understand. This simplicity is also why so much time and effort has been spent focusing on this type of actuation, and why elastomers are discussed more than any other material.

Remember we mentioned that subcategories of this include hydraulic and pneumatic actuation. We will now look at the strengths and weaknesses of these two actuators. After that, we will discuss a little bit more about certain challenges and solutions that apply to FEAs in general.

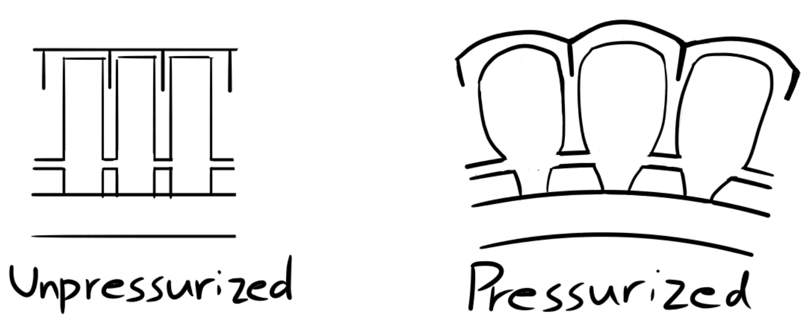
Pneumatic actuation

Pneumatic actuation has been given substantially more love than its counterpart. In fact, we will discuss some specific designs that have been made for this actuation method. But why is it popular? For starters, gases are lightweight and compressible. This has less impact for stationary robots that remain constantly tethered, but mobile robots only have capacity to carry so much. gases also provide rapid actuation as they can fill up space quickly.

Now let's discuss some of its drawbacks. You need high pressure to operate it. They are also very difficult to control, and not just due to the high pressure requirements. The pressure control tends to be highly non-linear. Its compressibility also has its flipside as it amplifies the issue of nonlinearity.

PneuNets

Pneumatic networks (PneuNets) are simply an application of FEAs [22]. You essentially have a collection of pneumatic channels in series, parallel, or both, all working together. The channels themselves are not very big. Instead, the pockets lining the walls of the materials have been increased in size to maximize the impact the gases have when applying pressure.

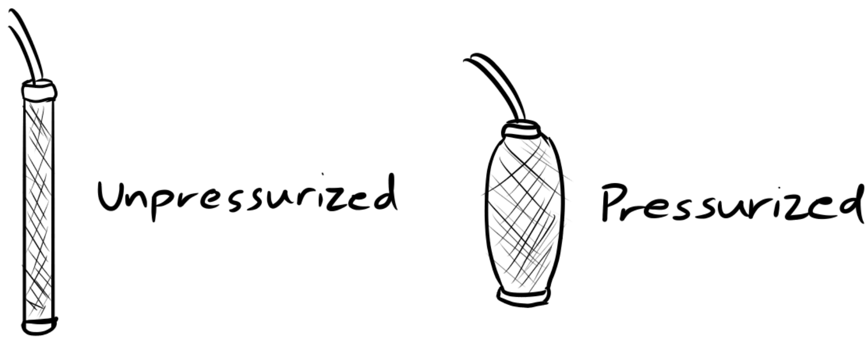


Outside of this, there is not that much more to say about this actuation method. The core concepts of varying its internal geometry still very much applies. Reinforcements can be added to ensure that movement only happens in the desired direction, and so on.

Pneumatic artificial muscles (PAMs)

Pneumatic artificial muscles (PAMs) are a more interesting application of pneumatics [23]. This one actually does not need to use elastomers! The important part is that the material still has enough elasticity to stretch itself. Braided fabrics could for instance be used.

Like the name implies, PAMs try to replicate the function of a muscle. A muscle works by contracting in length when pressure is applied, and instead expands radially. You can easily test this by flexing your biceps.



PAMs have incredible strength, can react quickly, and have a good force to mass ratio. Creating one PAM actuator is also really easy. But there is one big caveat. Like muscles, PAMs only allow expansion and retraction in one direction. This is equivalent to one muscle tendon. That means you need several of these things to create complex movements. Additionally, they only act under tension. The moment they lose tension, they buckle and collapse in on themselves.

Hydraulic actuation

There aren't any specific designs for using hydraulic actuation, and really, there is not too much to say about this one. Hydraulic is preferred over pneumatic actuation in cases that require higher forces, such as when operating heavy machinery. They are incompressible, which makes them a bit easier to control than gases. In terms of listing its benefits, this is about as far as we can go.

Now for the challenges when working with hydraulics. They tend to be a bit more viscous than gases, which give them slower response times. Not only that, they are also much heavier. Besides the issue of slower response, its weight limits the usage of such actuation, especially for mobile robots.

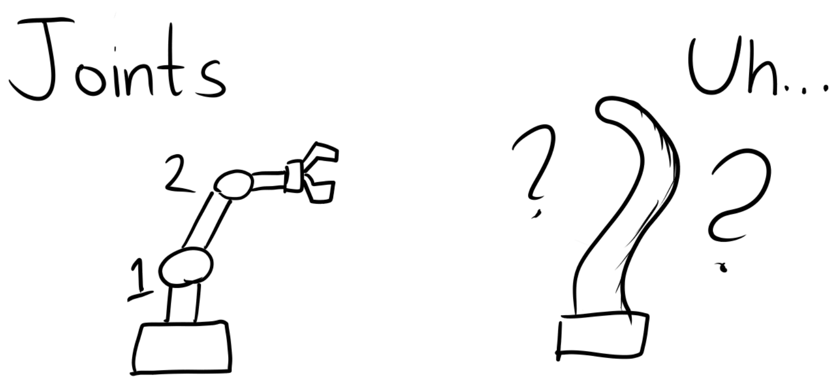
The challenges of FEAs

All in all, these actuators are great because of the simplicity of their concepts. But there are some considerable challenges that apply to FEAs and similar actuators. We discussed these as individual points for pneumatic and hydraulic actuation, but pressure generation is probably one of the greater issues working with FEAs. Adding what is essentially a battery for storing the pressure increases the weight considerably. More efficient storage methods need to be developed to deal with this issue. There are a few interesting research papers that tackle this. One paper tried adding a combustion chamber to supply pressurized air to the material component [24]. This method is actually really cool. Here, you are basically controlling your robot with the help of controlled explosions.

Another point that needs to be addressed is the nonlinearity of FEAs. This is definitely a big one. It is very difficult to model the characteristics such as the speed of the movement based on the output force provided. But here is the greatest challenge of them all: They have theoretically infinite degrees of freedom.

The movements of conventional robots can easily be explained based on the number of joints that it has. These joints can only move a certain way, with the most elementary ones being rotation and translation. Each of these elementary joint movements add one degree of freedom to your robot. Let's say you want the end effector (hand) of the robot to move to a certain spot. You do some fancy mathematics and lots of matrix operations to derive the different angles that each joint requires.

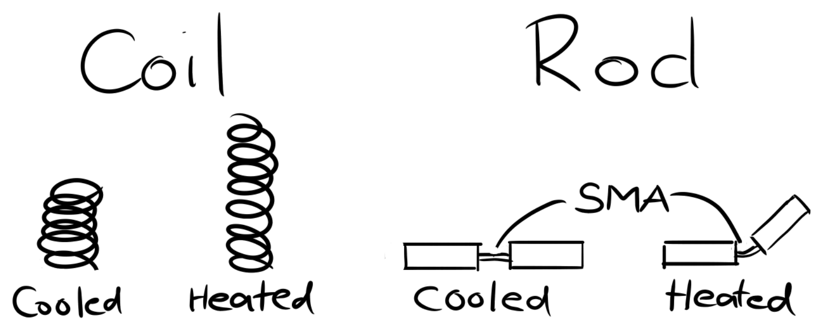
Looking back at our FEA, where are the joints? What type of math do you do to solve for the desired configuration? When solving for the conventional robot, every joint you solve for takes into account all the other joints of the robot. But here, you cannot really specify that, so you do solve it with regards to the infinite other flexing parts?



Sadly, no one has managed to come up with a proper solution, at least not yet. For now only simple, repetitive motions tend to be modelled, such as an (almost) linear extension of the FEA or an elbow bending motion [9]. This is with the aid of CAD software as well. So yeah, this part of research is still very much in development.

Shape memory alloys (SMAs)

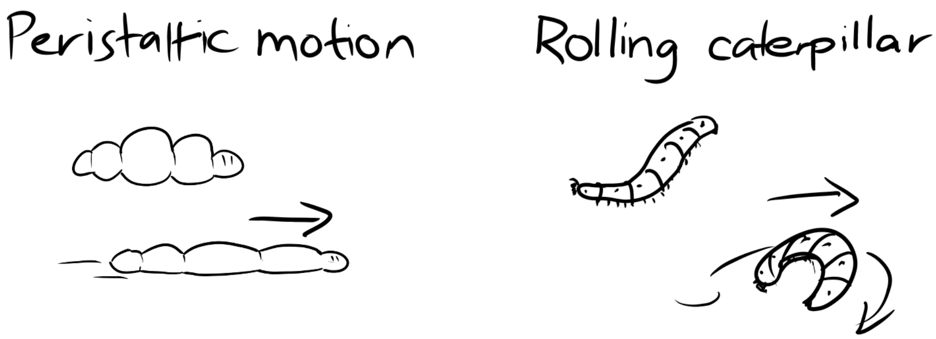
Shape memory alloys can be kind of confusing. Are they a type of material or a type of actuation? The answer is yes to both. Also, they are sometimes referred to as shape memory actuators [25], which does nothing for the abbreviated term but is definitely easier to refer to when written out fully. As we mentioned earlier, SMAs rely on thermal energy to alter their state. When heat is applied, their structure changes in such a way that they release stored elastic energy. Thus this actuator has a more explosive movement, which is very useful in situations that require really fast response times. This is one of the biggest advantages of using SMAs over FEAs, but there are other reasons as well. FEAs have a limit to how small you can make them. At some point, it becomes almost impossible to pass the fluid through the internal chambers. You do not have that limitation with SMAs as the actuation happens entirely within the material itself. Finally, SMAs are capable of generating large displacements due to their geometric design.



The amount of force these actuators can produce is partially reliant on the amount of thermal energy input. This energy needs to be regulated well, as too much heat could deform the actuator and cause permanent damage. Controlling SMAs is actually relatively straightforward due to its linear response.

But now we move on to their downsides. Despite the fast response times, the recovery period of SMAs is not the best as they have to cool back down to their resting state. They are also not very power efficient due to heat dissipation.

There are some really interesting applications of SMAs within soft robotics. One of them is the meshworm [26], where they use nickel titanium (NiTi) coil actuators to achieve peristaltic motion. Another one is the GoQBot ([27], which leverages the explosive capabilities of SMAs to create a rolling motion similar to an escaping caterpillar. This one is actually very cool in concept. SMAs in general have also been considered for use in creating artificial muscles, although research within this has been limited. As can be seen from the examples, the experiments tend to only be conducted on a smaller scale.



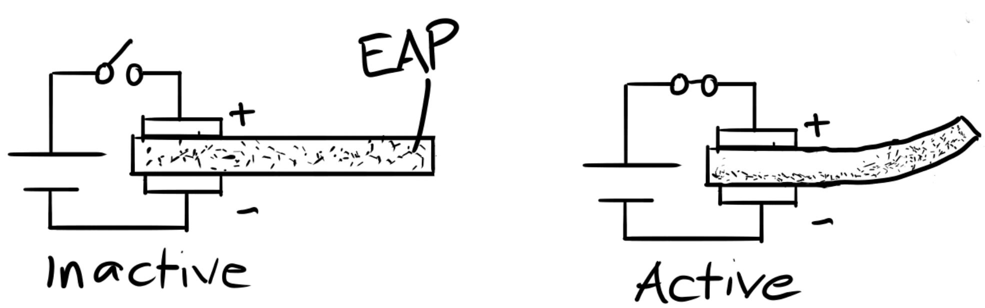
Shape memory polymers (SMPs)’

SMPs have lower densities and stiffness compared to SMAs. They have much faster recovery rate and are naturally compliant, but also have less explosive power in comparison. They are also biocompatible and are therefore better suited for medical applications [13], [28]. As mentioned, these are still experimental. One big challenge that they currently have is the unpredictability of their behavior. They are also non-linear in nature, so they are quite difficult to control even if you somehow manage to keep them predictable.

With that in mind, it is definitely something that has garnered interest from researchers. It remains to be seen how far this type of actuation will be developed.

Electroactive Polymers (EAPs)

Electroactive polymers (EAPs) have become all the rage within soft robotics. These are soft actuators that can be activated through the stimulation of an electric field, which causes the material to deform. This type of actuation has been given a lot of attention because they in theory mimic the same actuation mechanisms as biological muscles [29]. EAPs have also shown to have relatively high performance metrics.



It is also preferable to reduce the complexity of soft systems as much as possible. Electronic components and computation is already a necessity in most applications. Having an actuation mechanism that uses electrical power as well is therefore a big plus.

EAPs can come from different types of materials, two of which are ionic polymer metal composites (IPMCs) and dielectric-electrically actuated polymers (DEAPs). I never fully understood how exactly these materials work, but the dumbed down answer is that they are electrically sensitive polymers.

EAPs do sound all good and all, but they do have a few problems as well, like anything else. They require relatively high voltages for them to function. They struggle with regards to long-term durability and are prone to electromechanical instability. And as is the bane of most of these actuation methods, they are also nonlinear. Great. To top it all off though, the biggest issue is that most of these actuators have not been used outside of controlled laboratory environments [8], [28].

So yeah. EAPs are very very cool in concept, especially when it reaches a point where it can replicate the function of a muscle. But until then, EAPs need more time cooking in the oven.

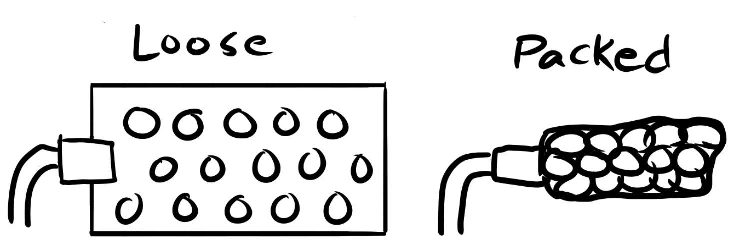
Variable stiffness

Technically speaking, SMAs already employ variable stiffness in its design. What we cover here then is a more *unique* case of such an actuation method. Although, it is almost dubious to call actuation. You'll see why.

Particle jamming

Particle jamming is very interesting. It does not actually produce any actuation by itself. Most of the time it would be employed in something like FEAs, where filler particles are loosely added within the internal chambers of the material component [30]. This gives it a fluid-like state and allows the body to move around. Upon reaching the desired configuration, vacuum is applied which causes the particles to pack themselves firmly and reach a solid-like state. One interesting application of this is with the design of a gripper [31]. This allows the body to conform to a wide variety of shapes and objects. Another unique application of particle jamming is the one presented in this paper known as the JSEL [32]. Cells that can be jammed and unjammed are put to use such that the fluid inside of the body is forced to move in a certain direction. Honestly, this design is extremely clever.

Alternatively, they can be used to lock the shape of the body such that it can support a larger amount of weight. And that's about it.



Outside of the JSEL, it is kind of unclear how else this “actuation” method really functions. And that is why it kind of blurs the line of actuation. In some ways it can be thought of as a supplement instead to support structures that are too soft. They kind of come with their own caveats as well. They add a lot more complexity to the overall robot, they add more weight, the particles may be spread out unevenly, and the list goes on. But hey, you never know when you might need this, so it’s better to have it around than ignoring its existence completely.

Wrapping it all up

And there we have it. Actuation at its finest. I think it’s clear to see here which actuation methods have been given the most attention. If you were to look up pictures and videos of soft robots, you will likely encounter FEAs the most. However, it will be interesting to see the progression of this field, especially with further developments within EAPs. EAPs hold the hallmark for what sci-fi enthusiasts imagine the future to look like.

We are not done yet though, and you will see why.

How long has it been now? A year? Maybe even longer. But things are looking up. It seemed grim at first, splitting research into so many different fields. But results are starting to show and your team is livelier than ever. Everyone is admiring each other’s work, with some people having gotten far enough to even come up with their own little contraptions. One managed to create a robot making use of FEAs. Its body whipped back and forth as explosions occurred within itself. Another one made a worm that could roll on the ground like its life depended on it, using the clever properties of SMAs. The list goes on and on.
And yet, there is something missing, but you cannot quite put your finger on it...

Sensors

Are we not there yet?

That must be it then. We have reached our end goal. But wait, there's more! It is indeed true that we can control our robot (given the electronics I guess). If you actuated it, it would work. You can see that it works. But, what if you are not looking at your robot? How can you say that it is moving the way it is supposed to? That it is in the proper configuration? For that we need sensors. We will not delve too deep into this topic, but it is important to understand its importance.

Again though, this is a soft structure. Despite having "soft" in its name, it makes everything way, way harder. So let us set some criterias for what we need in our sensors [33]:

- They need to be compliant
- Dimensions need to be limited
- Resilient and durable to survive large strain and deformation cycles
- Need to endure interaction with the outside world
- Fabrication methods and materials should ideally be able to integrate the sensing elements directly into the body of the robots

Thankfully, all kinds of sensors exist that can satisfy these requirements. And these are pretty much the same sensors we are used to seeing everywhere as well. So now, we will look at how these measure up when tested against soft robots.

Resistive and piezoresistive

These sensors measure the resistance variations that happen when the geometry changes. They require relatively simple electronics and are quite flexible, which makes integration relatively easy. However, they do not have the best performance. It is kind of hard to measure the resistances of the materials when they *do* change. Oh, and they are… *nonlinear*.

Capacitive

These measure the capacitance when the body changes. These sensors have really good performance. And they are linear! Can you believe that? Unfortunately they are *too* sensitive and can easily be affected by their environment. Surprisingly, they have not been used that much within soft robotics yet even though tactile technology is relatively well developed.

Optical

These ones detect light variations when strain or pressure is applied to a light transmission medium such as optical fiber. These also have excellent performance. Additionally they are not easily affected by environmental contaminants. Sadly they do not stretch that much, are really expensive and difficult to make, and really difficult to integrate.

Magnetic

This one requires two components; a permanent magnet, and something that can sense magnetic fields. You separate these two. When the material body moves, the magnetic sensor measures the change from the permanent magnet. These sensors are cheap, flexible, have good performance, and sadly are also easily affected by external interference. They sense magnetism after all, and well, there is a surprising amount of it all around us.

Inductive

These measure the inductance variations by some transducer mechanisms (coils, magnetic reluctance etc). These are also cheap, have good performance, and resistant against external interference. They are almost perfect, but they are difficult to set up.

A little more about sensors

Man, they all sound rather disappointing the way they have been described there. They are far more impressive than I make them out to be, and I would highly recommend the paper that explored this side of soft robotics [33]. They are just not quite there *yet*. Alright, so which ones do we choose? That is up to the user, really. There are currently no best practices on what types of sensors to choose, how many you should have, or even if they can sufficiently describe the configuration of your robot. Sadly, not a lot of research has been done on proper integration of these things, which showcases just how early in its life cycle soft robotics is.

Ethics and soft robots

Now, let us take a step back and discuss something a little different from the facts and numbers that we have gone through so far. This one is a little bit more loose and informal, owing to the fact that these are more opinion-based. And that is with regards to the ethics that surround soft robotics. Up to this point, we have only discussed actuation and the things needed to achieve that. When it comes to ethics, we have to take a more birds-eye view of soft robotics as a whole. Because well, you can't really raise too many concerns about actuation itself.

Medical sector

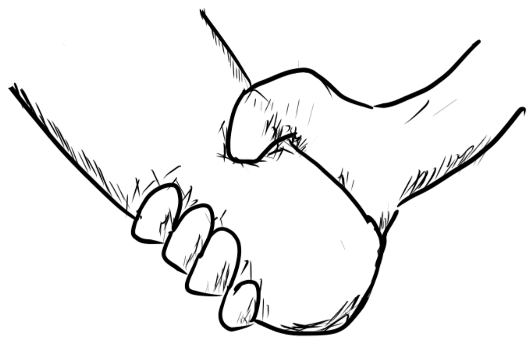
To date, not a lot of ethical questions have been raised about soft robotics directly. There are some concerns within the medical field, but these are not exclusive to soft robots [34]. As one of the targeted use-cases of soft robotics is surgery for instance, who do we hold responsible if something goes wrong? If a doctor uses a robot and it fails during the procedure, do we blame the tools, or do we blame the surgeon? At what point can we feel comfortable to use these technologies for such tasks as well? It is certainly a considerable leap from the conventional equipment we have available, especially when taking into account how "unpredictable" some of these actuation methods still are.

More humanoid robots?

I think it is fair to say that one of the ultimate goals of robotics is to create something with the same capabilities as us humans, to mimic the same movements we can, and even think the way we do. That last point draws a lot of controversy, and is somewhat outside the scope of what we are discussing here. Instead, soft robotics here would deal more with the physical aspects of this creation. Undoubtedly, robotics has come far in terms of its development. But looking around, we still struggle to replicate a lot of motions that we deem natural. Even the most advanced robots have that telltale sign of stiffness in their movements; we cannot really explain it, but we can definitely tell when you see it with your own eyes. One paper has a lot of positive outlook into what soft robots can do to improve these areas [35]. Another paper has a more cautious outlook at this [36], for how much more "natural" would these soft robots be compared to the conventional ones. At least with what we have developed so far, it seems there is no significant difference in the way we perceive these robots. Granted, these are not full-fledged humanoid shaped creations, but rather individual limbs of each type.

How about social interaction?

Let us delve a little more into the social aspect of soft robots. Despite the results of the previous study, I think we can agree that soft robotics will still contribute to the development of more socially interactable robots. The intrinsic safety of having a soft body inevitably leads to touch becoming a key factor of interaction between these creations [37]. Touch is, whether intentional or not, one way we humans are able to create attachments and relationships with other humans and even objects. The simple act of a child hugging a stuffed animal is an example of such an attachment.



But now, we have added autonomy to it as well. And this is perhaps a point that a lot of people find scary and unnerving. Some can easily draw the line and simply consider these things as man-made creations with no feelings and thoughts of their own. Others might create this attachment to them, and humanize them to an extent. But is this necessarily something wrong? One concern some have is that if they can emulate the sense of physical contact, some people may no longer want or need “real” human contact.

There is one particularly strong image discussed within [37] about the case of sex robots. This one is definitely sure to turn the heads of many people. But looking at it from a more neutral standpoint, it has some considerable real-world implications, and whether we like it or not, soft robotics is definitely a contributing factor.

Perhaps it is all still too early

I will not go much more into detail about this topic in particular, and I feel like we have gotten enough food for thought when it comes to some of the ethical concerns surrounding soft robotics. In the grand scheme of things, it is far too early to see how relevant these things will become. After all, I am sure that up until this point, you have probably never heard of soft robotics.

The end of the road… for now

"Do you think we can describe it now?"
"Hmm. I guess there is only one way to find out. Chuck it in the other room."
Just when you thought you had gotten there. And here you thought actuation was hard. Ah well, such is the way sometimes. Still, you are getting close… hopefully.

Also, what will people think when you finally do get it out into the world? Will they come to love it? Resent it? Would you be the one to blame if something goes wrong? Hmm… the farther you get, the more you've come to think of these things. You can still remember the strange expressions people had when you first started thinking about all this. Will that ever change?

Perhaps you have just been rushing into this, thinking it would be easy, and perhaps that was a little foolish. For now, it looks like that vision is still some ways off. But your team is still all here, and you aim to push forward. For this will truly be the future of robotics.

And with that, we wrap up our dive into the world of soft robotics. As you can see, there are many things left unanswered, but that is just how it is when a new field emerges. The most exciting thing about it is how much interdisciplinary work it inspires. It's a field where biology, chemistry, electronics, control, mechanics, and so much more all take part, where everyone is able to learn from others and progress this field into the future. And that future may be just as we imagined at the beginning, as the soft, round, and bulbous figure heads home towards its master, maybe carrying a bag of groceries in each wavy, tentacle-like hand.

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