[Title Page – Plant Inspired Soft Actuators] Hi! I'm Milena Nutrobkina with my counterpart, Elizabeth Slowik, and today we'll be talking with you about Plant Inspired Soft Actuators.

[Plant Structure Inspired Actuators] Actuators are responsible for moving and controlling other systems when they are activated. Some examples in nature are pinecones opening when moisture is present, the uptake of water in plant stems, and Venus fly trap activation due to pressure. Soft actuators, like hydrogels, have been developed for therapeutic purposes in surgical applications. However, hydrogels lose their mechanical strength under excessive swelling. A solution to this problem is to utilize closed-celled, fluid-filled systems, like plants, that can swell without any reduction in mechanical stiffness. Using this as our motivation, we tried to synthesize a soft composite to represent plant tissue analogs (PTAs) that could potentially be used as actuators.

[Synthesis of Closed-Celled polyHIPES] This composite is made of emulsified saltwater droplets into PDMS, a two-part polymer formed from intersecting polymeric chains, that is stretchable and allows water to pass allowing swelling to occur. The actual mechanics by which the experiment is run is through fluid movement driven by osmotic potential. To synthesize, first, PDMS and hexane are mixed together to form the outer phase. An aqueous phase of either salt water or glycerol is emulsified with the outer phase to form a Low Internal Phase Emulsion. After centrifugation, a High internal phase emulsion, or PolyHIPE, is synthesized in order to be used as an actuator.

[Goal] There were two main goals for this investigation. The first was to investigate the maximum swelling ratio from different compositions of the plant tissue analogs. The osmolyte concentrations change by varying the salt or glycerol in the sample while the microstructure changed by varying cavity wall thickness and cavity size. The samples can be measured by swelling in deionized water until the sample ceases to swell or ruptures. The second was to create a geometry that will allow for the PolyHIPE mixture to act as an actuator. Different concentrations of plant tissue analogs can be combined to form a unique structure. This structure can contain parts with varying stiffness to have a motion-like feature.

[Maximum Swelling Limitations for Cylindrical Geometry] The first part of the experiment was to investigate the maximum swelling structures of the PTAs. Due to the semi-permeability, these PTAs are osmotically active and can swell upon water intake due to a difference in chemical potential while maintaining cellular rigidity. The left plot shows the PTA swelling pattern with varying salt concentrations as the aqueous phase. As the concentration increases, swelling increases. Likewise, the right plot shows a similar result as well as that glycerol swellings almost double the amount that of the salt swellings. This experiment used 33% glycerol as the aqueous solution. It can be seen from the two plots that using glycerol as the aqueous phase has a higher osmotic potential and therefore drives the swelling further even at low concentrations, which leading to rupture. Based on this explanation, this is why we chose the salt as the aqueous concentration, to have less ruptures as the PTA swells.

[Plant Tissue Analog Synthesis] To synthesis PTAs, an outer phase was emulsified with an inner phase of either glycerol or salt and nanoparticles to synthesis fluid-filled polyHIPEs. From the maximum swelling limitation analysis, it was determined that the best aqueous phase to use was only with salt. The mixture was then centrifuged to get high droplet density. The high-density droplets were spread into a mold on top of non-emulsified PDMS to cure. This is important because the bi-layer structure works by allowing the PTA to swell over a non-emulsified polymer allowing for actuation to occur. Lastly, the cured PTA were cut into the desired shape and swelled in deionized water.

[Plant Tissue Analog Soft Actuators] The top left photo displays the sample after centrifugation. This is the first part where the high-density droplets from emulsion can be distinguished. The middle photo shows the sample spread into a mold on top of semi-cured PDMS. The whole sample was then cured before it could be cut into shape. The right photo shows the two different layers of the PTA. The bottom layer is just PDMS while the top layer contains the cured emulsion, which is where the actuation occurs.

[Effects of a Bi-layer Structure] This sample highlights the differences between simply swelling a sample and using PDMS to turn the sample into a soft actuator. As shown in the schematic diagram for this sample, the left side was only the cured emulsion. On the right side of the sample, the cured emulsion was placed on top of semi-cured PDMS. The picture on the left shows what the sample looked like after it was cut into shape. The picture on the right shows the effect of swelling the sample in deionized water. The front part of the sample that is lying flat corresponds to the side without PDMS. As it swells, it takes in the water to become bigger and taller, but the initial shape remains intact. The part of the sample that is curled corresponds to the half of the sample that was initially made on top of semi-cured PDMS. This difference in stiffness on the right side of the sample is what allows for movement to occur, in addition to the increase of size from swelling.

[Soft Flower Actuator Fabrication] The geometry for this actuator was in the shape of a flower or a star. The longer legs to the geometry give them more freedom and allow for more actuation to occur. Upon swelling, this actuator successfully folded up resembling a flower. The center of the flower stayed flat, creating a base for the actuator to sit on, and the curvature was so pronounced that it almost created a closed sphere.

[Soft Wave Actuator Fabrication] One actuator pattern was designed to have a wiggle motion when swelled. The top schematic shows the side view of the mold with red being the PTAs and the black lines represent a thin barrier at an angle between the two materials to have a wave motion occur. The bottom left shows a cured sample prior to swelling. The bottom right shows the swollen wave pattern.

[Soft Spherical Actuator Fabrication] Another geometry that produce was a sphere. This shape is desired because it can be used for drug delivery systems. The left figure shows that the PTA was cut in an eight-armed snowflake. More arms mean more actuation. Therefore, the right figure showed the swollen PTA as a sphere. Even though the desired result was produced, one of the arms still ruptured.

[Future – Soft Hinge Spherical Actuator] One of the solutions to the rupturing problem is to create hinges out of PTAs rather than a whole layer using the schematic on the right as inspiration.

[Future – Self Closing Soft Cube Actuator] In the future, we would like to synthesize a time actuated box where we utilize the hinge method to make a cube using the structure on the left as inspiration.

[Summary] Overall, actuators were created by combining different PTAs in a variety of geometries with spatial variations in PTA stiffness or concentration to have a bending or twisting motion. Under swelling, the PTAs self-assembled into a sphere, mimicked twist motion, and time delayed wiggle action. Therefore, we have created biocompatible, flexible, and robust soft composites that can act as actuators, especially in applications where mechanical performance is of utmost importance. In the future, we would like to test the amount of force these actuators retain as they swell as well.

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