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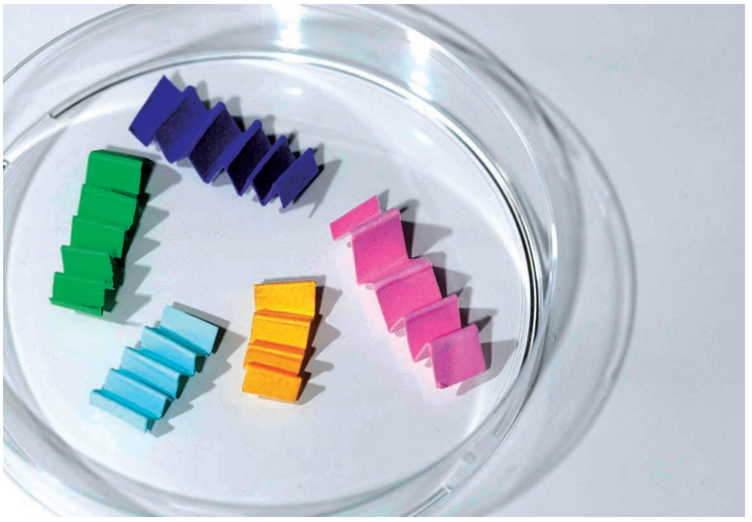

SOFT ROBOTICS

The art of folding

Designing artificial muscles with multiple degrees of freedom is a major challenge in the field of soft robotics. To mimic the properties of human skeletal muscles, it is necessary to create high forces with soft materials and have fine control over complex motion. Now, Robert Wood and colleagues, writing in the *Proceedings of the National Academy of Sciences*, report a fluid-driven artificial muscle, inspired by the art of origami, which can perform complex multiaxial motion while generating high forces.

Origami is the art of folding paper into different structures, and it provides the basis for the function of the fluid-driven devices developed by Wood and colleagues. These artificial muscles comprise three main components: a skeletal structure; a flexible skin and a fluid medium. The skin is sealed around the skeleton, which enables operation under an applied vacuum. This reduction in pressure leads to motion of the system, with the type of motion depending on the shape of the skeleton. "Using our simple architecture of an origami-based folded skeleton and soft skin, we can achieve large strengths in low-weight artificial muscles, derived from the combination of folding of the skeleton and tension in the skin," explains Wood, "the folding pattern of the skeleton then programmes the motion, which can go well beyond simple contraction." For example, simple zig-zag shapes lead to linear contraction, and complex out-of-plane motions combining torsion and contraction can be achieved using the origami Miura fold, a fold that is based on tiled parallelograms. If the stiffness of the connections of the pattern elements is varied throughout the skeleton, a pseudo-sequential motion can be generated; for example, to individually programme three fingers of a robotic hand for gripping, lifting and twisting of an object. This could be particularly useful for robots operating in close interaction with humans, such as in medical devices or when helping patients in hospitals.

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The researchers have explored a range of materials for the different components of the artificial muscle, varying in elasticity and internal channel structure, to optimize the performance of the device. Various fabrication techniques, such as 3D printing or casting, can be employed for the construction of the skeleton, and air and water have been tested as the fluid medium. For example, a linear zig-zag actuator with a nylon skin provides an actuation stress of ~600 kPa and a contraction ratio of ~90%, which exceeds the values reached by a human skeletal muscle. Polyester-based devices have been further demonstrated to be able to lift objects heavier than their own weight in less than 1 second.

The origami-inspired artificial muscles are energy efficient and produced from cheap materials. "The cost is extremely low; roughly a few dollars per actuator," remarks Wood, "and vacuum-based operation makes the system safe through reducing the risk of bursting inherent to positive pressure actuators." However, there are still limitations to overcome before these artificial muscles can be used for untethered operations, such as wearable exoskeletons. "The primary challenge for our design is the need for a pump, controllable valves and associated drive electronics to control fluid flow", comments Wood. The researchers are currently working on the improvement and characterization of the system, and they are developing representative demonstration examples, such as soft-yet-strong manipulators and multi-functional end effectors, to leverage the strengths of this approach in soft robotics.

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ORIGINAL ARTICLE Li, S. *et al.* Fluid-driven origami-inspired artificial muscles. *Proc. Natl Acad. Sci. USA.* http://dx.doi.org/10.1073/pnas.1713450114 (2017)