Onions can bend, contract and elongate just like muscles

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Bioinspiration or biomimetics is a field which deals with the study of the structure and function of biological systems for the designing and fabrication of materials, devices and machines[1]. Biomimetics can offer new potential for designing devices with novel abilities by simply replicating nature or natural phenomena. An actuator is a kind of motor which is responsible for moving or controlling a definite mechanism or system. It can be operated by any energy source, typically electric current, hydraulic fluid pressure or pneumatic pressure and converts that energy into motion.

The three basic actuation responses, i.e. contraction, expansion and rotation can be combined together within a single component to produce other types of motion. 'Artificial muscle' is a common term used for materials or devices that can reversibly contract, expand or rotate within one component due to an external stimulus like voltage, current, pressure or temperature. Conventional motors and pneumatic linear or rotary actuators do not meet the criteria as artificial muscles, because there is more than one component involved in the actuation.

Soft actuator has now become an emerging research area with a wide range of versatile applications, especially in the field of robotics. Unlike the conventional actuators like electric motors, pneumatic or hydraulic actuators which are always rigid and heavy with limitation in degrees of freedom, soft actuators are normally made of soft materials and also can generate pre-designed motions. Another outstanding feature of soft actuators is the multiplicity in the degrees of freedom, both active and passive, enabling them to mimic bio-motion which is absent in conventional actuators.

Different soft materials such as dielectric elastomers, electrostrictive polymers, conducting polymers, ionic polymer–metal nanocomposites, carbon nanotubes and nanoporous composites have been utilized for further development of actuators in recent times[2–5]. These types of actuators are competents of either bending or contraction/elongation with the help of external stimulation and are known as soft actuators. The soft actuators are often referred to as artificial muscle due to the above-mentioned property. At present, scientific research is focused towards the development of artificial muscles. Lin *et al.*[6] had demonstrated compartmentalized dielectric elastomers as soft actuator which are capable of bending. However, it is difficult to fabricate these actuators on a large scale and they cannot simultaneously contract/elongate and bend. Several researchers are involved in the fabrication of artificial muscles[7–9]. Bio-inspired actuators, which are commonly known as artificial muscles, have potential applications in robotics, biomedical devices and micro-electro-mechanical systems (MEMs). Han *et al.*[7] fabricated bio-inspired graphene actuators by unilateral UV irradiation of graphene oxides. Carbon nanotubes and graphene-based bio-inspired electrochemical actuators are now popular times. Ismail *et al.*[9] carried out the fabrication of an electrochemical actuator from chitosan/polyaniline microfibres using an *in situ* polymerization technique. This electrochemical actuator can behave like artificial muscles. However, there are no artificial muscles available which can simultaneously perform elongation/contraction as well as bending as of now.

Chen *et al.*[10] recently developed an ideal artificial muscle from the gold-plated onion epidermal cells, which consist of corrugated upper and lower cell walls in latticed arrangement. They developed this artificial muscle by simply modulating the constant driving voltage. Unlike other types of artificial muscles, onion cells coated in gold can expand or contract to bend in different directions depending on the driving voltage applied.

Onion epidermal cells can be easily disconnected from the rest of the body, in spite of being one cell thick with dimension between 20 and 30 μm. Figure 1 *a* shows the process of removal and preparation of the onion epidermal cells. In this process, a single layer of onion epidermal cells was taken from the core-facing side of a fresh peeled onion and it was washed with water. The reliability of the actuator becomes unfavourable due to the presence of water in the cell interior. However, long-term cell dehydration due to spontaneous water evaporation would generate irregular corrugations, rupture and pin holes on the cell walls. Therefore, a freeze-drying treatment for 24 h was employed for the removal of water in the cell interior without collapsing the cell walls (Figure 1 *b*). These cells are of irregular size, packed tightly together and rectangular in shape as shown from the SEM images

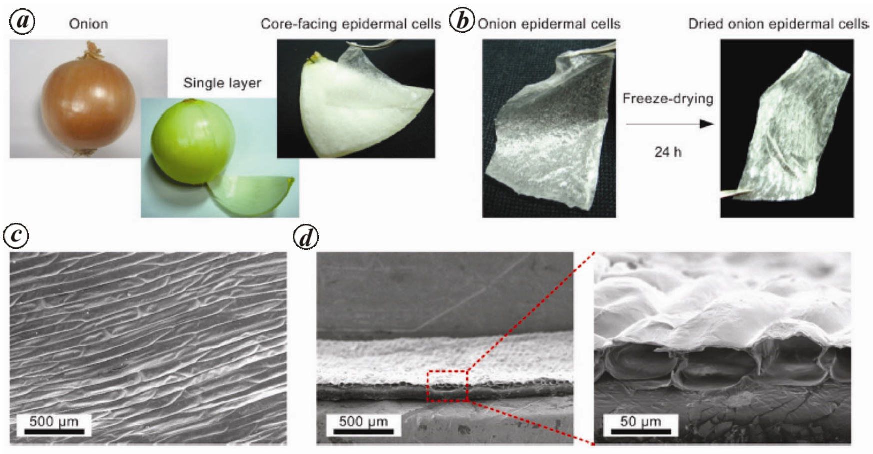

Figure 1. Schematic diagram of the onion epidermal cells. ***a***, Obtaining the onion epidermal cell layer. ***b***, Photographs of the cell layer before and after freeze-drying for 24 h. ***c***, Top-down SEM image of the cells post freeze-drying (scale bar = 500 μm). ***d***, SEM image (side view) of the cells after freeze-drying (left-hand side: scale bar = 500 μm; right-hand side: scale bar = 50 μm). (Reprinted with permission from Chen *et al.*[7] Copyright (2015) AIP Publishing LLC.)

obtained after freeze-drying (Figure 1 *c* and *d*). The cell walls are strong enough to provide support and protection for the cells, and remain so after the complete removal of water. The freeze-drying process keeps the microstructure of the onion epidermal cells integral, but also brings rigidity and fragility. Naturally, the cell walls are made of 21% cellulose, 36.6% hemicellulose and 42.4% pectin, in which the cellulose and hemicellulose are separated by water. The entanglement between cellulose and hemicellulose fibrils as the cells dry out obstructs the cells to be driven in elastic deformation. The hemicellulose fibrils are considered to play a key role in controlling elongation of the cell wall. The dried cells can be made elastic by an acid pretreatment using 1% sulphuric acid to remove hemicellulose from the cell wall. Gold at different thickness was sputtered on both sides of the onion epidermal cell layer for converting the processed onion cell into an actuator. The gold layers were intentionally deposited at different thickness for developing diverse bending stiffness on the upper and bottom cell walls to make the bending actuation more prominent.

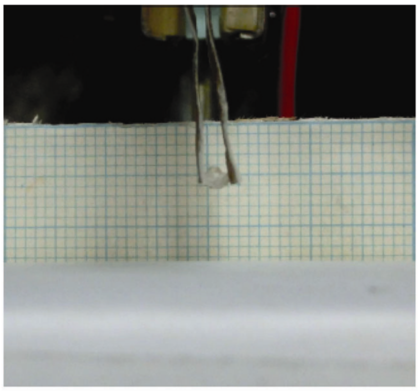

Figure 2. Tweezers made of onion artificial muscle. (Reprinted with permission from Chen *et al.*[7] Copyright (2015) AIP Publishing LLC.)

By modulating the magnitude of the voltage, the artificial muscle made of onion epidermal cells would deflect in opposing directions while either contracting or elongating. At voltages of 0–50 V, the artificial muscle elongated and had a maximum deflection approximately of 30 μm. At voltages of 50–1000 V, the artificial muscle contracted and deflected 1.0 mm. The maximum force response was 20 μN at 1000 V. They had also demonstrated a potential application of the fabricated artificial muscle obtained from onion cells by combining two onion artificial muscles to act as tweezers, which gripped a small cotton ball of around 0.1 mg in weight (Figure 2).

The plant epidermal cells are cheap, can be easily obtained, are environment-friendly and cost-effective. Due to the diversity of plants and their cell structures, discovering the use of natural structures in engineering is of interest in recent times. For instance, plant epidermal cells like onion epidermal cells have a unique structure that modulating the magnitude of the applied voltage will cause bending in different directions due to electrostatic attraction. It is important to mention here that animal cells will not work with equivalent treatment as they do not possess cell walls. Absence of cell walls in animal cells makes them ineligible for the fabrication of bio-inspired artificial muscles, as there is no support and protection of cells from the cell walls after the long freeze-drying treatment.

It is expected that this bio-inspired artificial muscles can be potentially applied in the field of actuators and provide excellent biomedical applications. One can expect that the efficiency of this muscle can be improved by enhancing the maximum displacement and output force, while simultaneously minimizing the applied voltage.

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