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Artificial muscles for jaw movements

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ABSTRACT

Facial expressions in humanoid robots play an important role in improving the interactions between human beings and machines. Jaw movements are key components in facial expressions especially during talking and singing activities. In this paper we develop artificial muscles for jaw movements, using dielectric elastomer actuators with embedded plastic fibers. The soft actuator can avert electromechanical instability and achieve a linear strain of 48%. The actuators are installed in a robotic skull to drive jaw movements, at the positions similar to those of the masseters in a human jaw. The experiments show that these artificial muscles can achieve periodic jaw movements with displacements and velocities comparable to those achieved by natural muscles. The actuators can also achieve jaw movements with various amplitudes and frequencies, mimicking the human singing (or talking) activities. The present studies demonstrate that dielectric elastomer actuators are capable of achieving accurate and controllable deformations/movements, which is significant in the applications to soft and biomimetic robots.

Humanoid robots, that resemble human beings in physical appearance, have become more and more interesting recently, due to their extensive applications to nursing, reception, child tutoring, and old people serving [1–3]. Facial expressions in humanoid robots play an important role in improving the interactions between human beings and machines. Jaw movements are key components in facial expressions especially during talking and singing activities.

The human jaw movements are driven by a complex assembly of muscles which include temporalis, masseter, digastric (Fig. 1(a)), medial pterygoid muscles and lateral pterygoid muscles [4]. To achieve jaw movements and other facial expressions in a humanoid or masticatory robot, various actuators were employed, including electric motors [5], piezoelectric actuators [6], shape memory alloys [7], and McKibben pneumatic actuators [8]. These smart actuators have their respective advantages and can effectively create human-like mastications or facial expressions. However, they exhibit some disadvantages. For example, electric motors and piezoelectric actuators may need accessory mechanical units to transmit movements. Consequently, the whole actuation systems are usually complicated and bulky. Shape memory alloys usually consume large electric energy, since their actuation mechanisms are related to large electric current and temperature change. Pneumatic actuators generally require the transfer of large volumes of gas for actuation and consequently exhibit slow actuation rate. Optimal design of pneumatic networks may achieve rapid actuation (say, in 50 ms) [9]. In this project we investigate artificial muscles for jaw movements, by using dielectric elastomer actuators (Fig. 1(b) and (c)). Recently the emerging field of soft robotics offers the prospect of applying soft actuators as artificial muscles in the robots, replacing traditional actuators based on hard materials (say electric motors or piezoelectric actuators) [9–14]. Dielectric elastomers are one class of soft actuators, which can deform in response to voltage and can resemble biological muscles in the aspects of large deformation, high energy density and fast response [15–17].

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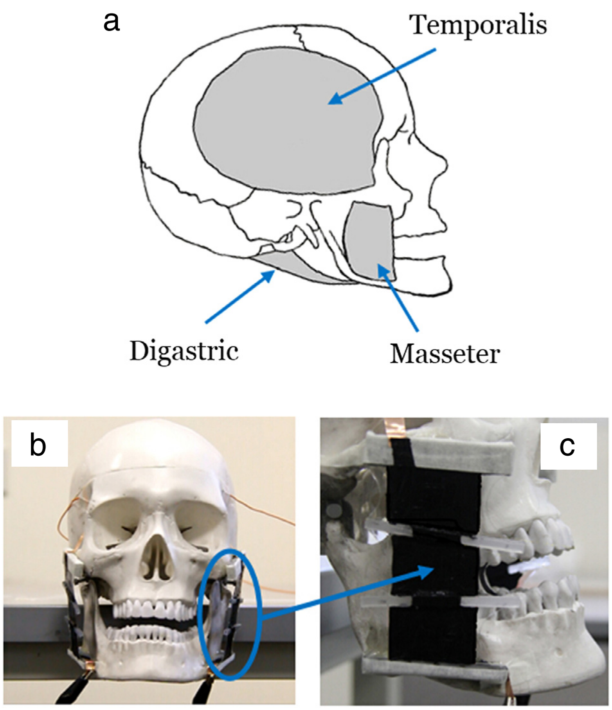

Fig. 1. (a) Schematic of natural muscles to achieve jaw movements. (b) A robotic skull with artificial muscles. (c) Artificial muscles made of dielectric elastomer actuators.

In this paper we develop an artificial muscle which can achieve a linear strain of 48%, by placing plastic fibers on the surfaces of a dielectric elastomer actuator. The soft actuators are installed between the cheek of a robotic skull and the lower jaw (Fig. 1(b)), at the position similar to those of the masseters in a human jaw (Fig. 1(a)). The experiments show that these artificial muscles can achieve periodic jaw movements with displacements and velocities comparable to those achieved by natural muscles. The actuators can also achieve jaw movements with various amplitudes and frequencies, mimicking the human singing (or talking) activities. The present studies demonstrate that dielectric elastomer actuators are capable of achieving accurate and controllable deformation, which is significant in the applications to soft and biomimetic robots.

Fig. 1(b) and (c) show the dielectric elastomer actuators in the robotic skull. We fabricate and install the actuators as follows. A membrane of a dielectric elastomer (VHB 4905, 3M) has a length (L_2) of 10 mm, a width (L_1) of 30 mm, and a thickness (H) of 0.5 mm at the stress-free state. The membrane is then subject to a horizontal prestretch $\lambda_{2p} = 4$, and the two boundaries along the horizontal direction are fixed to two rigid clamps, each of which has a length of 50 mm, a width of 10 mm, and a thickness of 5 mm. The rigid clamps are made of acrylonitrile butadiene styrene (ABS) and are fabricated by a 3D printer. The two clamps are then fixed to the robotic skull, as shown in Fig. 1(b) and (c). One is attached to the cheek, and the other attached to the lower jaw. The self-weight of the lower jaw makes the membrane prestretched in the vertical direction. Due to the configuration of the robotic skull (Fig. 1(c)), the two clamps may not be parallel to each other, and the initial inner and outer lengths of the membrane (at voltage $\Phi = 0$) are 57 mm and 62 mm, respectively. That is, the average prestretch in the vertical direction is about $\lambda_{1p} \approx 2$. In order to maintain the horizontal prestretch in the middle of the membrane, two plastic fibers made of polypropylene (PP) are placed on the surfaces of the membrane. Each plastic fiber has a length 50 mm, a width of 3 mm, and a thickness of 1 mm. The separation between the adjacent clamp and fiber is about 20 mm (Fig. 1(c)). Compliant electrodes made of conductive carbon grease are then smeared onto the two surfaces of the dielectric elastomer. When subject to voltage, the dielectric elastomer actuators expand, and the jaw rotates around two mechanical joints (see Fig. 1(c)). These two joints mimic the human temporomandibular joints (TMJs, literally the joints between the temporal bones of the skull and the condyles of the mandible, see Fig. 1(a)), via which the lower jaw is pivoted at the two sides of the jaw [18,19].

The embedded plastic fibers can greatly improve the performance of the dielectric elastomer actuators. Fig. 2(a) plots the applied voltage as a function of the jaw displacement (i.e. the vertical displacement of the lower central incisor). The black or gray curve represents the performance of the actuator with or without the plastic fibers, respectively. Compared to the actuators without the fibers, the actuators with the fibers have much smaller curvatures in the inner and outer edges (see the two insets in Fig. 2(a)). In the experiments, we increase the voltage with a ramp rate of 10 V/s, and measure the jaw displacement by a laser sensor (ILD1700, MicroEpsilon). The two curves terminate when the actuators suffer the failure of dielectric breakdown. As shown in Fig. 2(a),