3D PRINTED, PROGRAMMABLE OSMOTIC ACTUATORS FOR ORTHODONTIC APPLICATION

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ABSTRACT

We have successfully demonstrated (1) a 3D fabrication and packaging scheme that can readily convert hydraulic actuators into autonomous osmotic actuators, and (2) a new type of osmotic actuators that can generate desired locomotion and force outputs for orthodontic application. Soft bellow structures are employed to realize and amplify the actuation, including elongation, contraction, bending, and twisting. When placed in oral cavity, the actuators are osmotically pressurized to move and guide the teeth into proper alignment in a steady and preprogrammed manner. Besides pumping, it is demonstrated for the first time that osmotic actuation can be tailored to realize sophisticated functions.

INTRODUCTION

Conventional orthodontic treatment typically employ wires of shape-memory alloy or plastic aligners to guide the movement of teeth [1]. The forces applied on teeth are not steady, usually rise abruptly right after each adjustment (or replacement) and fall slowly afterwards. The periodic actuation could cause the distress of many patients, and potential delays throughout the orthodontic treatment. Up to now, a variety of miniature actuators based on diverse physical and chemical operating principles have been fabricated and investigated for their potential applications in the biomedical field. Most existing miniature actuators are driven by electricity, and their power consumptions are usually proportional to the designated force and pressure outputs. For applications such as implantable systems that need to operate for long periods of time, it is challenging to satisfy the electricity requirements because of the corresponding space and safety issues. Currently, only limited progress has been achieved, especially for applications demanding high pressure and large force outputs.

Osmosis is a passive transport mechanism widely found in biological systems. When an osmotic actuator is placed in an aqueous medium, it drives water to generate the required pressure gradient for fluid pumping. Previously, it was utilized in drug delivery systems [2] and microfluidic chips [3] to pump various fluids. In addition, it was used to guide the process of distraction osteogenesis [4]. Osmotic actuation is attractive because it is constant rate, high pressure and requires no electricity for operation. To address the need for orthodontic devices with steady and programmable outputs, this work presents a 3D fabrication and packaging scheme that realizes osmotic actuators with elaborate locomotion and force characteristics. Soft bellow structures are used to realize and amplify the actuation, including axisymmetric ones for elongation and contraction, asymmetric and helical ones for bending and twisting, respectively. As such, osmotic actuators can serve as powerful orthodontic devices, and treatment with great comfort and performance can be realized.

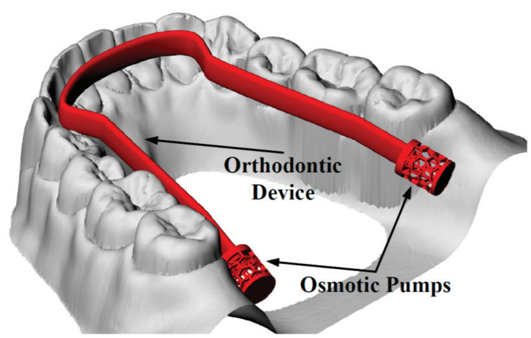

Figure 1: Working scheme of osmotic orthodontic actuator.

OPERATING PRINCIPLE

Figure 1 illustrates the working scheme of osmotic orthodontic actuator. It is mainly a hollow structure filled with osmotic solution and mounted on the lingual side of teeth. At each end of the actuator, there is an osmotic pump consisting of a semipermeable membrane sandwiched by honeycomb structures, as shown in Figure 2. The operation of the osmotic actuator is based on the concentration-gradient induced, net water flow across the semipermeable material. Water can be drawn either into the actuator from its surroundings, or out of the actuator to an external reservoir. Typically the concentration and therefore the osmotic pressure inside the actuator is higher than that of the outside environment. In case that water needs to be driven out of an osmotic actuator, the hollow structure will be filled with pure water and a bellow-type reservoir filled with super-saturated solution will be mounted around the semipermeable membrane, as illustrated in Figure 3.

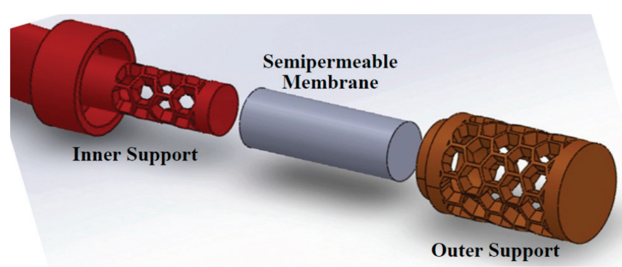

Figure 2: Exploded view of an osmotic pump.

In our miniature osmotic actuators, a so-called breathable polymer, which allows only water molecules to diffuse across, is employed as the semipermeable material. This material is a thermoplastic, so it can be shaped into desired geometry by various thermal forming processes that heat the material up to 220˚C with the application of a pressure up to 5 MPa. The net water flow rate across the breathable membrane is proximately proportional to the thickness and effective semipermeable area of the membrane. For a thin membrane that results in a high water flow rate, it needs to be supported by honeycomb structures on both sides. The void fractions of the honeycomb structures determine the effective semipermeable area of the membrane. Another major factor that effects the net water flow rate across the semipermeable membrane is the osmotic pressure gradient across the membrane. It is preferred to maintain the pressure gradient at a constant level, so the net water flow rate throughout the actuation period remains constant as well. Usually super-saturated solutions are used, whose osmotic pressures remain at maximum over the actuation period.

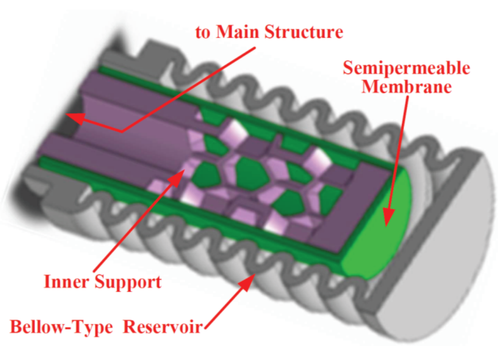

Figure 3: An osmotic pump with built-in reservoir.

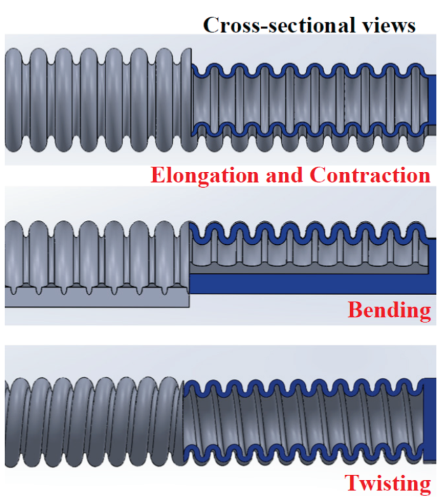

Figure 4: Bellow structures used to generate the basic actuation required in orthodontic treatment.

The required actuation in orthodontic treatment are the combinations of contraction, elongation, bending, and twisting, which can be realized by the elastomer structures shown in Figure 4. Soft bellow structures, which are commonly utilized to generate locomotion by folding and unfolding the excess materials, are employed to realize and amplify the actuation. For axisymmetric bellows, the changes of their inner pressure result in 1D translational motions. The changes of inner pressure result in rotational and bending motions of helical and asymmetric bellows, respectively. Because of the nonlinear nature of both the rubber-like material and the resulting large deformation, it is challenging to analyze and design these actuators. We are currently working on the modeling of these actuators through analytical, numerical and experimental approaches, and characterize their locomotion and force outputs as functions of their inner pressure as well as geometrical and material parameters. COMSOL simulation is utilized to facilitate the analysis, design, and optimization of these soft bellow-type actuators. The cross section of each bellow unit is defined using ellipse with two radii equal to 0.4 mm and 0.3 mm, which is perpendicular and parallel to the axis of the main structure, respectively. The length and outer diameter of the main structures is chosen to be 25 mm and 4 mm, respectively.

FABRICATION AND PACKAGING

The actuator is fabricated employing DLP (Digital Light Processing) stereolithography. The main structure is composed of a photoactive resin (Spot-E, Spot-A Materials) and photo-polymerized layer by layer using a 3D printer (MiiCraft, Young Optics). The X and Y resolution of the 3D printer is down to 30 µm and the Z resolution is down to 10 µm. The photo-polymerized structure has a Young's modulus of 12 MPa, an elongation at peak of 65%, and a Shore-A hardness of 65. For the soft bellow structures to sustain a pressure difference up to 2 atm, the minimum thickness is found to be about 200 µm.

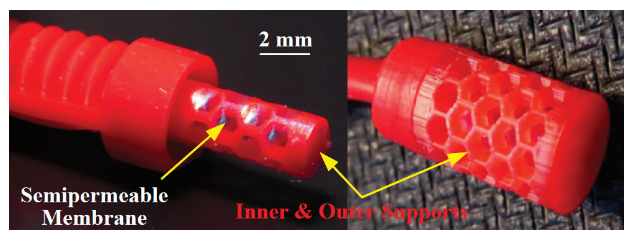

Figure 5: Photographs of a fabricated osmotic pump.

The semipermeable material employed in the miniature actuator is a certain type of vapor-permeable, thermoplastic polyurethane (TPU, DINTEX FT-1880, Ding Zing Chemical Products). The material is received in the form of 15 µm thick sheets, and shrink wrapped (in one minute) on the inner support to build a 3D and completely sealed interface. Hot air with a temperature up to 150˚C is used to seal the thermosplastic sheet on the supporting structure. A fabricated osmotic pump is shown in Figure 5. The net flow rate of water across the breathable/semipermeable membrane is found to be 5.2 µl/(hr·mm^2) according to Figure 6, when a planar semipermeable area of 15.9 mm^2 and a super-saturated PEG 400 solution is used in the measurement. If a super-saturated NaCl solution is used instead, the net water flow rate cross the same membrane drops 20% to 4.15 µl/(hr·mm^2). It is also verified that the sealing of the membrane assembly can sustain a pressure difference up to 2 atm. The diameter of the inner and outer support is 2 mm and 4 mm, respectively. The length of the supports is 8 mm, while the effective semipermeable area is 30 mm^2. If a thicker semipermeable membrane is used, it is expected that the membrane can sustain a higher pressure difference while the net water flow rate across it will be lower. By thermal laminating layers of 15-μm-thick sheet together, semipermeable membranes with desired thicknesses can be formed.

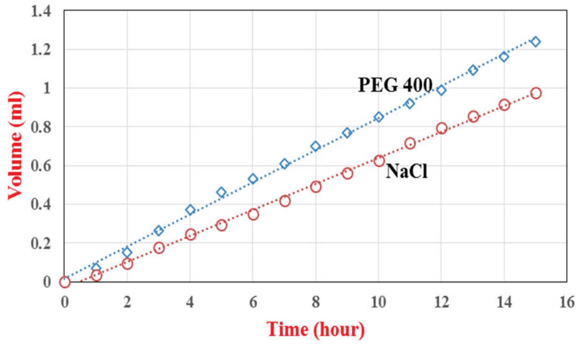

Figure 6: Water permeability of breathable membrane

RESULTS AND DISCUSSION

The force required to move a tooth depends on the type of tooth movement. Usually it is in the range between 20 to 120 grams [5]. To measure the force output, a customized fixture with integrated force sensor and water tank is employed. All the soft bellow structures demonstrated in this work were powered by osmotic pumps with an effective semipermeable area of 30 mm^2. Pure water and supersaturated PEG 400 solution are used to create a constant pressure gradient across the semipermeable membrane, so the net water flow rate into or out of these soft bellow structures is expected to be 156 μl/hr. Figure 7 shows the outputs of an axisymmetric bellow with a length of 25 mm, an outer diameter of 4 mm, and a wall thickness of 250 μm. This bellow is designed to generate elongation or contraction when positive or negative pressure is applied, respectively. Its inner pressure rises to 2 atm in 90 minutes, which results in a force output of 62 grams or up to 100 grams by increasing the pressure or cross-sectional area. When a negative pressure (vacuum) is applied, the maximum contraction is 9.4 mm, which is 37.5% of the original length. If it is free to deform, the elongation rate of this axisymmetric bellow is 10.4 mm/hr. Overall, the inner pressure, deformation and force outputs are linearly proportional to the actuation time.

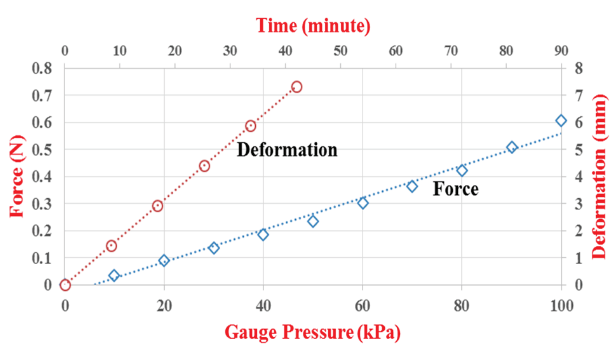

Figure 7: Outputs of an axisymmetric bellow

Figure 8 shows the outputs of an asymmetric bellow, whose photographs are shown in Figure 9. This bellow can generate bending motion in both directions when positive or negative pressure is applied. It has a length of 25 mm, a semicircular cross section with an outer radius of 2 mm, and a wall thickness of 250 μm. It takes 225 minutes for the inner pressure to reach 2 atm, which results in a torque output of 0.326 N·cm. If it is free to bend, the initial curvature is 11.74 m^{-1} under its own weight. In about 100 minutes, the curvature rises to 75 m^{-1}, which corresponds to a radius of curvature of 1.33 cm. If a negative pressure (vacuum) is applied, the asymmetric bellow starts bending toward the other direction, and the maximum curvature is about 91 m^{-1}, which corresponds to a radius of curvature of 1.1 cm. Overall, the inner pressure, bending curvature and torque outputs are roughly linearly proportional to the actuation time.

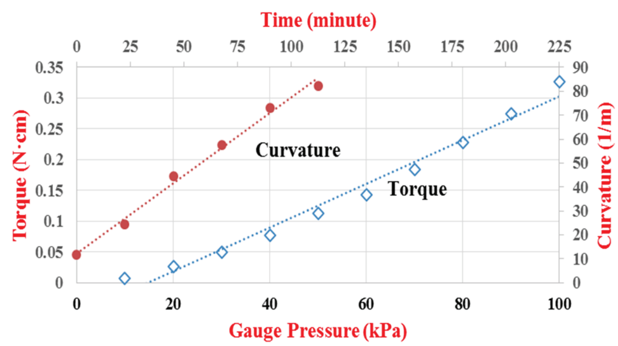

Figure 8: Outputs of an asymmetric bellow for bending

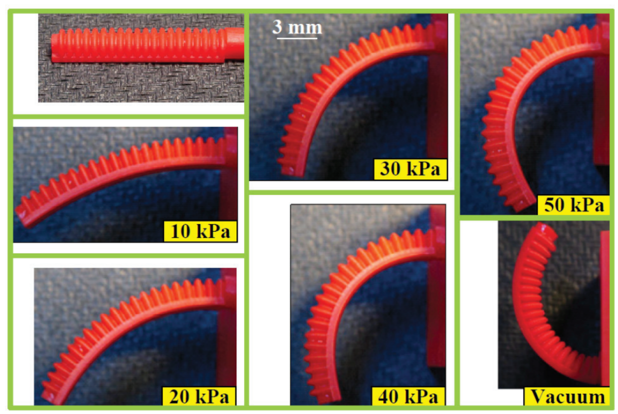

Figure 9: Bending of an asymmetric bellow under varying positive and negative pressure.

A composite bellow structure for leveling is also demonstrated as shown in Figure 10. Three asymmetric bellows are connected in serial, while the middle one has a bending direction opposite to that of the other two. If a negative pressure (vacuum) is applied, the central portion of the composite structure moves upwards, as shown in Figure 10. By rotating the composite bellow structure upside down, the moving direction will be reversed. Figure 11 shows the outputs of a helical bellow for twisting. It has a length of 25 mm, a circular cross section with an outer diameter of 4 mm, a wall thickness of 250 μm, and a helical pitch of 1.2 mm. In 100 minutes, the helical bellow rotates for 120˚ between its two ends while its inner pressure rises to 1.75 atm. If a negative pressure (vacuum) is applied, the structure will rotate around the opposite direction. The maximum torque that the helical bellow can generate is measured to be 0.62 N·cm while its inner pressure rises to 1.8 atm. Overall, the inner pressure, rotating angle, and torque outputs are linearly proportional to the actuation time. By integrating the four basic types of bellow structures together, pre-programmed orthodontic devices can potentially be realized.

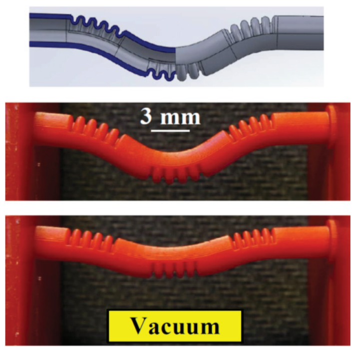

Figure 10: Photos of a composite bellow for leveling.

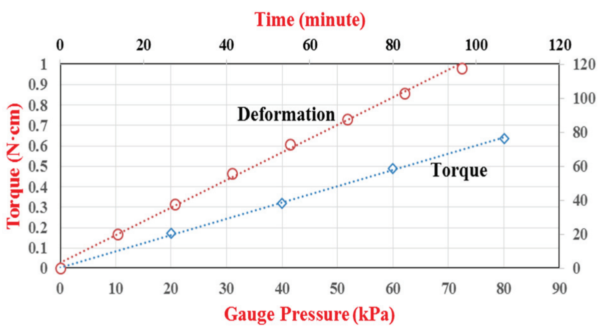

Figure 11: Outputs of a helical bellow for twisting.

The soft bellow structures demonstrated in this work have the highest actuation rates that we currently can achieve. They are much faster compared to the actuation rates typical employed in modern orthodontic treatment. By reducing effective area or increasing thickness of the semipermeable membrane, the net water flow rate in or out of the actuator and therefore the actuation rate can be reduced. Meanwhile the 3D, layer-by-layer printed hollow actuators are prone to leak because of structural defects and irregularities. If a thin elastomer layer (about 30~50 μm) with low Young's modulus and high elongation at peak is coated on the inner surface of the actuator, it is verified that the sealing can be significantly improved and the leakage can be largely prevented. The maximum allowed inner pressure and therefore the force or torque output of the actuator can be further increased. As such, the presented osmotic actuators can be further tailored to realize sophisticated characteristics and functions as desired. The material currently being used to fabricate the bellow structures is not biocompatible, so further surface treatment or new photo-active resin is required before the actuators can be placed in oral cavity for long period of time.

CONCLUSION

We have successfully demonstrated (1) a 3D fabrication and packaging scheme that can readily convert hydraulic actuators into autonomous osmotic actuators, and (2) a new type of osmotic actuators that can generate desired locomotion and force outputs for orthodontic treatment. Axisymmetric bellows are utilized to generate contraction and elongation actions, while asymmetric and helical bellows are employed to generate bending and twisting actions, respectively. When placed in oral cavity, the actuators are osmotically pressurized to move and guide the teeth into proper alignment in a steady and pre-programmed manner. In the prototype demonstration, osmotic bellows with a length of 25 mm, an outer diameter of 4 mm, a wall thickness of 250 μm and a structural period of 1.2 mm are fabricated and characterized. The effective semipermeable area of the osmotic pump is 30 mm^2, which results in a water flow rate of 156 μl/hr. It is verified that the sealing of the semipermeable membrane assembly can sustain a pressure difference up to 2 atm. For all the bellow structures, it is found that their outputs are roughly linearly proportional to the actuation time. As such it is demonstrated for the first time that osmotic actuators can be tailored to realize sophisticated functions and serve as powerful tools for orthodontic application.

ACKNOWLEDGEMENTS

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