Extreme Mechanics Letters 3 (2015) 89–104

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

Scalable manufacturing of high force wearable soft actuators

Huichan Zhao, Yan Li, Ahmed Elsamadisi, Robert Shepherd *

Sibley School of Aerospace and Mechanical Engineering, Cornell University, Ithaca, NY 14853, USA

ARTICLE INFO

Article history:
Received 1 January 2015
Received in revised form 25 February 2015
Accepted 26 February 2015
Available online 28 February 2015

Keywords:
Soft robot
Rotational casting
Elastomer
High force
Exoskeleton

ABSTRACT

For future applications of soft robotics, mass production of complex actuators that can apply high forces is necessary. In this paper, rotational casting is adapted as a new manufacturing method for soft actuators. The criteria for both mold design and material properties of the elastomeric precursors to produce networks of pneumatic channels are described. A cuboid soft actuator that can generate a force of >25 N at its tip, a near ten-fold increase over similar actuators previously reported is presented. Additionally, this manufacturing technique is used to fabricate a wearable assistive device for increasing the force a user can apply at their fingertips.

1. Introduction

Soft machines are emerging as a new component in robotics that allow for simpler operation of complex functions (e.g., robotic manipulators) [1–3], more natural motions [4–7], and new functions (e.g., climbing walls) [8]. In many cases, these machines are actuated by pneumatically powered balloons composed of elastomers [1–3,9,10]: increasing their inflated pressure results in greater stiffness and shape change. At low or zero inflation pressures, these actuators exhibit low stiffness and cause limited resistance to movement as wearable devices and human interfaces. As a result, there is a growing effort to use soft actuators for exoskeletons and prosthetics that can augment the force of, or altogether replace, human grasping and locomotion, as well as perform physical therapy tasks [11–13].

The McKibben muscle (a fiber-reinforced soft actuator) was developed over six decades ago and is capable of large ranges of stiffness as a function of pressure [14]; for example, Fluidic Muscle DMSP^{TM} (Festo, Inc.) can be inflated from 0 to ∼800 kPa (∼120 psi) [15]. This actuator, however, is limited in that it has only one mode of powered actuation: contraction. Other fluid powered soft actuators that are under development have many modes of actuation (bending, extending, and contracting) [16–18] but are fabricated laboriously, usually by replica molding [1,3], investment casting [19], or fiber winding [20]. The useful actuator designs from these processes are limited as replica molding is essentially a layup process, investment casting is costly, and fiber winding is practical in only very simple architectures. Additionally, replica molded actuators function by the expansion of thin elastomer membranes that burst at low pressures for the current choices of materials [21], and relies on adhesive layers that easily delaminate. For many future applications of soft robotics (e.g., prosthetics or therapeutic and surgical tools), mass production of complex actuator designs that apply high forces will be necessary.

In this paper, we describe the manufacturing process of soft actuators using rotational casting, a reliable and high throughput production method. We present criteria for both the mold designs and required material parameters of the elastomeric precursors. To demonstrate this method's utility, we rotationally casted a soft actuator that can generate a force of >25 N at its tip, a near ten-fold increase over similar actuators previously reported [12]. Additionally, we fabricated and tested a wearable, assistive device for increasing the force a user can apply at their fingertips.

* Correspondence to: 236 Thurston Hall, Cornell University, Ithaca, NY 14853, USA. Tel.: +1 607 255 8654.

E-mail address: rfs247@cornell.edu (R. Shepherd).

http://dx.doi.org/10.1016/j.eml.2015.02.006
2352-4316/

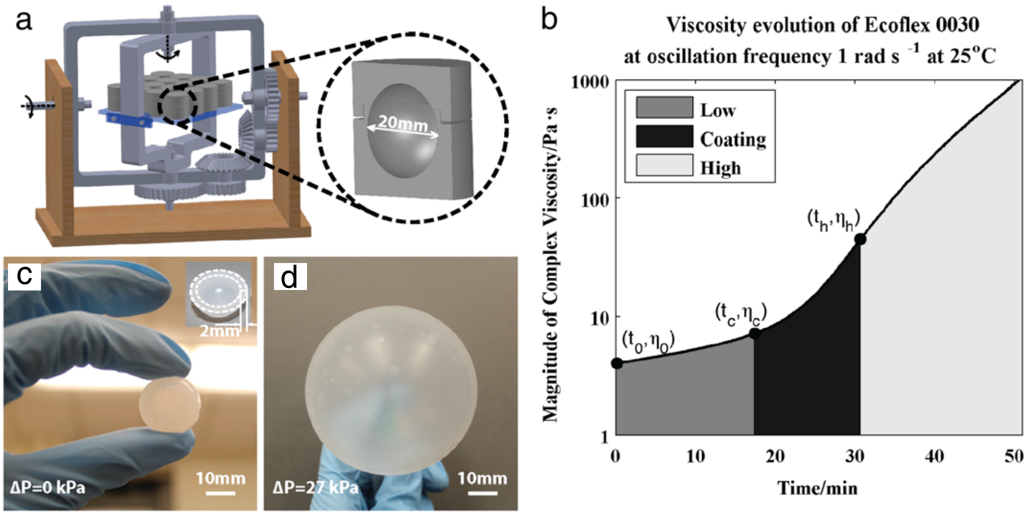

Fig. 1. (a) Biaxial rotational casting system with multiple spherical molds, (b) complex viscosity evolution of Ecoflex 0030 at oscillation frequency of 1 rad s^{-1} at 25 °C, (c) rotational cast spherical actuator with inset of cross-section, and (d) inflated spherical actuator at $\Delta P = 27$ kPa.

2. Experimental design

We chose to rotationally cast our actuators (Fig. 1) because it is an established process for high volume fabrication of hollow, monolithic structures (e.g., boat hulls and chocolate eggs). We used a 3D printer (Scholar 30, Objet, Inc.) to fabricate both the rotational casting machine and to rapidly iterate molds for the actuators. To compare our rotational casted actuators to existing ones, we used a similar design to elastomeric, pneumatic network (PneuNets) [1] and characterized them by testing their applied tip force at varying internal pressures at a fixed curvature. To fabricate force augmentation devices for a human hand, we designed soft actuators based on the shape of a finger.

To intuitively actuate the force augmentation device, we attached electromyography (EMG) sensors (Muscle Sensor v3, Advancer Technologies) to muscles in the forearm to trigger the finger actuators because they are low in cost and easy to implement. The electrical impulses detected by the EMG sensors open and close solenoid valves (Solenoid Air Directional Control Valve, McMaster) in line with the compressed air for powering the actuator. We chose a pneumatic power source because air is inviscid, thus can be delivered rapidly, and it can have an energy density similar to lithium polymer batteries for use in untethered operation [22].

Due to the complexity of the rotational flow fields of our viscoelastic precursors, we determined the dependence of machine and material parameters for fabricating a soft actuator using a simplified analytical model for Newtonian fluids and observing, experimentally, the flow conditions through transparent molds. We used Matlab® to simulate the trajectories of mold elements during rotation and used the results to determine the gear ratios in our machine to uniformly coat the interior of the molds. The rheological properties of the viscoelastic pre-elastomers we used were measured at an oscillatory frequency comparable to the strain rate of flows in our system using the Cox–Merz rule [23].

3. Results and discussions

3.1. Parameters of the rotational casting system

The majority of rotational casting processes use a frame with two axes of rotation to coat the interior of a heated, hollow mold. During rotation, a molten thermoplastic resin coats the mold surface, then the system is cooled until the material falls below its glass transition temperature and becomes stiff [24]. Though some thermoplastic elastomers may be compatible with rotational casting of soft actuators (e.g. Elastollan from BASF), the elastomers currently used in soft robots are cured using radical or condensation polymerization [1–5,7,9,12,13,16–22].

The rotational casting system we developed for fabricating soft actuators uses materials that are liquid at room temperature and polymerize into soft elastomers during the casting process. This system has four parameters that must be tuned: (i) viscosity evolution during casting; (ii) rotational speed of the primary axis, ω_x; (iii) axial speed ratio of the machine, r; and (iv) the internal surface geometry of the two-part molds.

As the elastomeric material gels, the viscosity increases towards infinity [25], and there is an increasing resistance to flow from external forces such as gravity, normal force and drag from the mold during rotational casting. Using rheometry, we have identified three important viscosity regimes for the rotational casting of thermosetting elastomers (Fig. 1(b)): *low*, when the initial viscosity, η_0, allows the material to flow too fast to rotate with the mold; *coating*, where the polymer has reached a threshold viscosity, η_c, large enough to spread along the interior surface; and *high*, when the gelling elastomer has exceeded another threshold viscosity, η_h, and no longer flows fast enough to uniformly coat regardless of the number of rotational cycles.

The lower threshold of the *low* regime flow rate is entirely dependent on η_0; however, the *coating* and *high* regimes are also dependent on the characteristics of the