INCREASING ELECTRORHEOLOGICAL RESPONSE IN HYDRAULIC ACTUATORS VIA SCALABLE MICROPATTERNED ELECTRODES

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ABSTRACT

The design, fabrication, and demonstration of an electrorheological valve that operates at reduced electric field are presented. An electrorheological liquid crystal flows between upper and lower electrodes. Applying an electric field aligns the liquid crystal with the field, increasing its apparent viscosity. Valves with conventional flat electrodes and patterned valves with 200 μm high protrusions on the electrodes are compared. The increase in apparent viscosity in patterned valves is about 2.5X greater than in valves with flat electrodes under the same average field. Patterned-electrode valves can potentially control hydraulic actuation of mechanically biomimetic soft robotic organs.

KEYWORDS

Electrorheological fluid, liquid crystal, ER valves, soft robotic

INTRODUCTION

Artificial organs that mimic the complex motions of human systems like the gut will speed the development of implantable and ingestible medical devices [1] by enabling initial testing in a mechanically biomimetic environment without the use of animal models. Although recent advances in soft robotic technology [2] have potential as organ system mimics [3], the size of the required pumps and fluid control valves limits the achievable actuation complexity, making it impractical to accurately mimic the intricate motion of human organ systems. To overcome this challenge, we propose a system of electrically-controlled microvalves based on electrorheological (ER) fluids (Fig. 1) that will be able to precisely control fluid flow from a central source to selectively actuate the small-scale hydraulic actuators, for example to mimic peristalsis. One challenge of such ER microvalves is the large electric field required to operate them, which necessitates some combination of narrow gaps (causing low flow rates) and high voltages. The present work focuses on the potential of a 3D electrode geometry and its resulting electric field concentrations to reduce the average electric fields required to operate the ER valve for future applications in soft robotic systems.

ER fluids display a change in apparent viscosity under the influence of an applied electric field. When integrated into a flow channel with a pair of top/bottom electrodes, these fluids can be used as a valving mechanism to turn flow off and on in hydraulic actuation systems. However, traditional heterogeneous ER fluids contain particles that limit their applicability in microscale systems due to sedimentation and clogging. Homogeneous liquid crystals (LCs) offer a potential solution. The liquid crystal 4-Cyano-4'-pentylbiphenyl (5CB) (Ambeed, Inc.) shows a strong ER response due to its rod-shaped molecules and positive dielectric anisotropy; its viscosity depends on the balance of torques acting on individual liquid crystal molecules [4]. When a strong electric field is applied perpendicular to the flow, the liquid crystals rotate to align with the field, increasing the apparent viscosity (Fig. 1). The use of liquid crystals in microvalves has been demonstrated in [5,6], but these studies used high fields of >1 kV/mm, with typical fields >2.5 kV/mm and some as high as 7 kV/mm [5]. To reduce the required field, the present valve features repeated protrusions on the electrode to locally concentrate electric field and increase applied electric torque. Together with 5CB's nonlinear electric field response, these enhancements can yield higher apparent viscosity at lower applied fields. The approach builds on [7], in which non-straight electrodes bounding the width of a channel concentrated fields to actuate heterogeneous, particulate-based ER fluids. The present work represents the first time that protrusions have enhanced ER fluid actuation in the height direction, where smaller gaps already enable lower voltages to create high fields, as well as the first use of a 3D-patterned electrode geometry in a non-clogging, homogeneous, liquid crystal ER system.

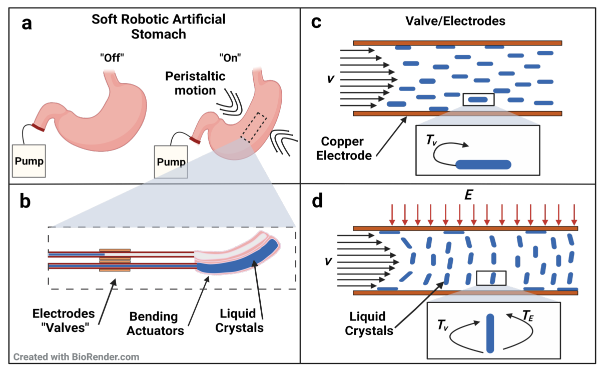

Figure 1: a) Diagram of soft robotic stomach with peristalsis; b) hydraulic actuator filling with LCs; c) fluidic torque aligns LCs with flow for low viscosity ("open" valve); d) electric field rotates LCs perpendicular to flow for high viscosity ("closed" valve).

EXPERIMENTAL

Copper electrodes/valves were 3D printed with a Markforged Metal X™ using a copper-based filament provided by Markforged, Inc., which is composed of copper powder and a polymer/wax binder. After printing, the wax is removed in a boiling Opteon SF-79 solvent bath, creating a semi-porous structure in the part that allows the remaining binder to be thermally debound in a sintering furnace. After sintering, the electrode is fully dense and only pure copper remains. Tape-cut polyimide sidewalls (142 μm, McMaster-Carr) complete the channels, set channel height together with any 3D patterning, and electrically insulate the electrodes. The patterned electrode features protrusions of approximately 200 μm height and 356 μm length separated by 356 μm spaces in the flow direction (Fig. 2). Each electrode plate also includes inlets, outlets, and holes for mechanical alignment pins that ensure correct registration of the two plates. The inter-electrode gap for the flat-electrode device is 426 μm based on the tape height. The effective gap between the electrodes for the patterned-electrode device reflects both its 284 μm tape thickness and the geometry of the 3D-printed protrusions and is confirmed through flow measurements.

The zero-voltage flow resistance and effective height of the patterned valve (with protrusions) are measured by connecting the patterned valve and the flat valve (without protrusions) in parallel to a syringe pump and weighing exiting flows with balances (Fig. 3a). The effective resistance of the patterned valve is calculated from the known resistances and measured flows. The effective height of the patterned valve is determined using the Poiseuille equation for flow in a rectangular channel. Because the flow's utilization of the available channel volume depends on flow rate, the measurement is repeated at different flow rates (Fig. 3b). At low flow rates, the measured resistance and effective height depend less on flow rate. The effective height of the channel at nearly full channel utilization is 525 µm, within the experimental uncertainty of its 484 µm nominal height given nonidealities in the printed protrusions. The inter-electrode gap is taken to be 525 µm, and the effective height is interpolated to determine the zero-voltage resistance of the patterned valve at each flow rate.

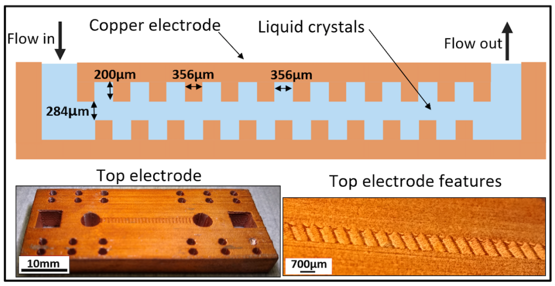

Figure 2: a) Schematic diagram of patterned electrodes; b) photograph of the top electrode; c) zoomed-in photograph of locally protrusions (fabricated as grooves) on the top electrode.

The patterned valve's effectiveness under applied electric fields from 0.2 kV/mm to 1.9 kV/mm is determined by monitoring exiting flow rates from the two parallel valves while applying the field across just the patterned valve (Fig. 3a). The flow circuit is analyzed to extract the patterned valve's resistance under electric field, and apparent viscosity is determined from measured resistance using the Poisseuille equation. The flat valve's effectiveness under electric field is determined similarly, by applying the field across the flat valve. The applied voltages are scaled by channel height to ensure equal electric fields.

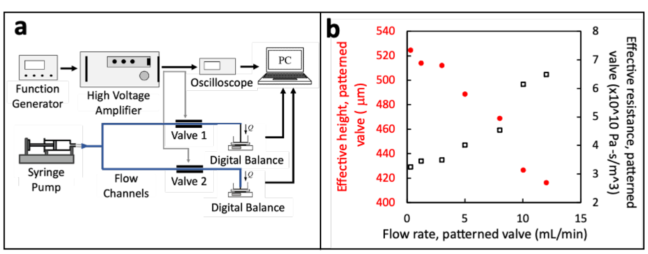

Figure 3: a) Diagram of experiment; b) Effective height (red) and resistance (black) vs. patterned valve flow rate.

RESULTS AND DISCUSSION

Fig. 4 plots the apparent viscosity vs. applied electric field for the patterned and flat valves for flow rates of 0.6 mL/min and 1.2 mL/min. The apparent viscosity of the patterned valve saturates at a field of less than 0.6 kV/mm, comparing favorably with the typically >2.5 kV/mm used in prior work [5,6]. The saturation value of apparent viscosity in the patterned valve is approximately 0.10 Pa-s, equal to 4.3X the liquid crystal's zero-field viscosity of 0.0234 Pa-s and similar to [4]. In contrast, the flat valve's maximum apparent viscosity is 0.060 Pa-s, just 2.6X the zero-field viscosity. Furthermore, the flat valve's maximum apparent viscosity is first observed at an electric field of 1.9 kV/mm, more than 3X greater than the saturation field of the patterned valve, and even then the flat valve's viscosity shows no evidence of saturation. Above 0.5 kV/mm, the valve with the 3D-patterned electrode yields on average 2.5X larger apparent viscosity than in the valve with the flat electrode; the difference is attributed to electric field concentrations at the corners of the protrusions and the nonlinear ER response of 5CB to electric field.

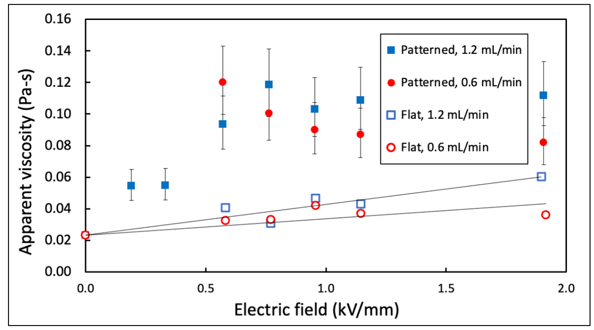

Figure 4: Apparent viscosity vs. field for patterned and flat valves at 0.6 (red) and 1.2 mL/min (blue). Lines are guides to the eye.

The patterned valve's height is the primary source of experimental uncertainty. If its height were larger than measured, the results would overestimate the field in the patterned valve and underestimate its performance relative to the flat valve. On the other hand, if the height of the patterned valve were smaller, the results would overstate the performance of the patterned valve. The effects of a ±30 µm height variation are captured in the error bars for the patterned valve. These experimental results suggest that in the future, ER valves with field-concentrating, 3D-patterned electrodes can be suitable for providing compact, integrated control of soft robotic actuation of organ system mimics for the testing and development of new medical devices.

REFERENCES

[1] K. Kalantar-zadeh, N. Ha, J.Z. Ou, and K.J. Berean, "Ingestible Sensors", *ACS Sens.*, 2, 468−483 (2017).

[2] J. Walker, T. Zidek, C. Harbel, S. Yoon, F. Sterling Strickland, S. Kumar, and M. Shin, "Soft Robotics: A Review of Recent Developments of Pneumatic Soft Actuators", *Actuators*, 9, 3 (2020).

[3] Y. Dang, Y. Liu, R. Hashem, D. Bhattacharya, J. Allen, M. Stommel, L.K. Cheng, and W. Xu, *Soft Robot.*, 3, 273-283 (2021).

[4] K. Negita, "Electrorheological effect in the nematic phase of 4-n-pentyl-48-cyanobiphenyl", *J. Chem. Phys.*, 105, 7837 (1996).

[5] T. Miyoshi, K. Yoshida, J. Kim, S.I. Eom, and S. Yokota, "An MEMS-based multiple electro-rheological bending actuator system with an alternating pressure source", *Sensors and Actuators A*, 245, 68–75 (2016).

[6] M. De Volder, K. Yoshida, S. Yokota, and D. Reynaerts, "The use of liquid crystals as electrorheological fluids in microsystems: model and measurements", *J. Micromech. Microeng.*, 16, 612 (2006).

[7] X. Huo and G. Yossifon, "Significant enhancement of the electrorheological effect by non-straight electrode geometry", *Soft Matter*, 15, 6455 (2019).

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