Lee *et al. Micro and Nano Syst Lett (2018) 6:1*
https://doi.org/10.1186/s40486-018-0063-4

Micro and Nano Systems Letters

LETTER

Open Access

Finger-triggered portable PDMS suction cup for equipment-free microfluidic pumping

Sanghyun Lee, Hojin Kim, Wonhyung Lee and Joonwon Kim*

Abstract

This study presents a finger-triggered portable polydimethylsiloxane suction cup that enables equipment-free microfluidic pumping. The key feature of this method is that its operation only involves a "pressing-and-releasing" action for the cup placed at the outlet of a microfluidic device, which transports the fluid at the inlet toward the outlet through a microchannel. This method is simple, but effective and powerful. The cup is portable and can easily be fabricated from a three-dimensional printed mold, used without any pre-treatment, reversibly bonded to microfluidic devices without leakage, and applied to various material-based microfluidic devices. The effect of the suction cup geometry and fabrication conditions on the pumping performance was investigated. Furthermore, we demonstrated the practical applications of the suction cup by conducting an equipment-free pumping of thermoplastic-based microfluidic devices and water-in-oil droplet generation.

Keywords: Polydimethylsiloxane (PDMS) suction cup, Finger-triggered equipment-free pumping, Microfluidic device

Introduction

Over the past few decades, microfluidic devices have emerged as an effective platform for various bio and chemical analyses (e.g., point-of-care testing [1], dynamic microarray [2–4], single-cell analysis [5–7]) because of their numerous benefits, including reduced fluid volume, rapid analysis, high sensitivity, massive parallelization, and portability. In spite of these benefits, the broad and practical utilization of microfluidic devices is still limited because of the necessity of bulky, complex and expensive external power-consuming equipment for fluid pumping (e.g., peristaltic, syringe, and pneumatic pumps). Accordingly, researchers have attempted to realize an on-chip micropump, instead of using an external pumping equipment, to minimize the system to provide device portability [8, 9]. However, the integration of pumping components (e.g., microvalves and diaphragms) is required to perform on-chip pumping with a microfluidic device, which increases the device fabrication complexity. Moreover, power-consuming bulky and expensive equipment and complicated tube connections for the operation of integrated pumping components are still required.

In this regard, various methods were developed to enable equipment-free microfluidic pumping, such as capillary- [10–12], gas- [13], degas- [14, 15], pumping lid- [16], and evaporation-driven [17, 18] pumping. These approaches offer simplicity of execution by eliminating the need for an off-chip equipment. However, the broad implementation of these approaches is still limited by complicated fabrication, narrow range of applicable device materials (e.g., hydrophilic material for capillary), and pre-treatment requirement (e.g., pre-degassing). Accordingly, 'finger-powered' pumping strategies have been proposed for more practical and field-applicable fluid driving approaches [19–22]. Although these approaches provide a simple operation with a human finger, they require complex and expensive device fabrication such as multi-layer photolithography and computer numerical controlled (CNC) milling process. Moreover, an accurate assembly of the fluidic channel part and the pumping actuation part is necessary, making the device fabrication more complicated. This is because the microfluidic device for the pumping operation using a human finger in these studies should be integrated with many

---

*Correspondence: joonwon@postech.ac.kr
Department of Mechanical Engineering, Pohang University of Science and Technology (POSTECH), 77 Cheongam-ro, Nam-gu, Pohang, Gyeongbuk 37673, South Korea

valve structures, which regulates the fluid flow (e.g., fluidic diode) under the pressure created by the human finger actuation. In addition, the finger actuation parts are irreversibly integrated with the microfluidic chip; hence, they cannot be used for other devices. With the aim of addressing the abovementioned limitations, this study presents a portable and power-free finger-triggered polydimethylsiloxane (PDMS) suction cup to generate the fluid flow in microfluidic devices. This method is very simple and easy, but effective and powerful. It offers the following benefits: (i) easy fabrication from a three-dimensional (3D) printed mold, (ii) easy-to-use and ready-to-use without any pre-treatment (e.g., pre-degassing), (iii) portable and facile assembly or disassembly, and (iv) broad application for various material-based microfluidic devices. To drive a fluid through the microfluidic channels, a user places the PDMS suction cup at the outlet of the device and dispenses the fluid at the inlet. The user then presses and releases the cup with a finger, thereby pulling the fluid toward the outlet. In addition, various pumping performances can be achieved by changing the cup geometry or fabrication conditions. An equipment-free pumping of thermoplastic-based microfluidic devices and a water-in-oil droplet generation using the PDMS suction cup were demonstrated herein for practical applications.

Materials and methods

Fabrication of a suction cup using 3D printed master mold

The suction cup was fabricated using PDMS and a 3D-printed master mold (Fig. 1). Male and female master molds were made by printing poly(lactic acid) (PLA) using a 3D printer (Makerbot Replicator 2, Makerbot). The PDMS mixture (base + curing agent, Sylgard 184, Dow Corning) was poured on the 3D printed female mold, assembled with the male mold, then cured at 70 °C in an oven. The cured PDMS was peeled off from the mold and cut using a razor blade. PDMS suction cups of different geometries (diameter and thickness) can also be fabricated by varying the dimensions of the 3D printed master mold.

Preparation of the PDMS- and thermoplastic-based microfluidic device

For the master mold preparation, a photoresist (KMPR 1025, MicroChem, Inc.) was spin coated on a 4 in. silicon wafer with a height of 50 µm, then baked on a hot plate at 100 °C. The patterns on a photomask were transferred onto the silicon wafer by UV light exposure, followed by post-exposure baking and removal of the unexposed photoresist using a developer (SU-8 developer, MicroChem, Inc.).

The PDMS-based microfluidic device was fabricated by replica molding. The PDMS mixture (10:1 w/w ratio of the polymer base to the curing agent) was poured into the mold, cured, and peeled off from the mold. Inlet and outlet holes were then punched using a biopsy punch. The prepared PDMS replica and the glass substrate were bonded to each other by air plasma treatment (CUTE-MP, FemtoScience).

The thermoplastic-based microfluidic device was fabricated through PDMS-based hot embossing. A PDMS stamp was prepared by double-casting the PDMS replica from the master mold. Both polystyrene (PS) and polymethylmethacrylate (PMMA) substrates were prepared (thickness: 2 mm). Plates of a laboratory hot press

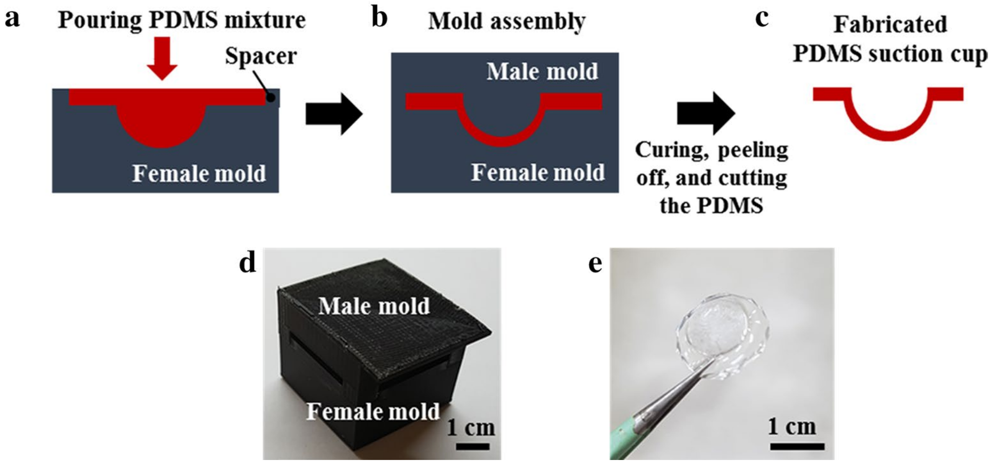

Fig. 1 Fabrication process of the PDMS suction cup, photographs of the 3D printed mold, and fabricated suction cup. **a**–**c** The PDMS mixture is poured in the 3D printed mold, cured, peeled off from the mold, then cut by a razor blade. **d** 3D printed molds for the PDMS suction cup fabrication. **e** Fabricated PDMS suction cup

machine (Qm900M_TD500, QMESYS) were heated to an embossing temperature of 145 °C. The materials for hot embossing were loaded on the heated plate in a stack consisting of a 4 in. silicon wafer, a thermoplastic substrate, and a PDMS stamp (from bottom to top). After 1 min, a force of 4.3 kN was applied to the stack at 145 °C for 3 min. The stack was then cooled down to 100 °C after 3 min and removed from the press. Subsequently, the embossed thermoplastic substrate was peeled off from the PDMS stamp. The embossed substrate was rinsed, dried, and bonded to a pressure-sensitive adhesive (3 M 9969, 3 M) using a roller to form a sealed microfluidic device.

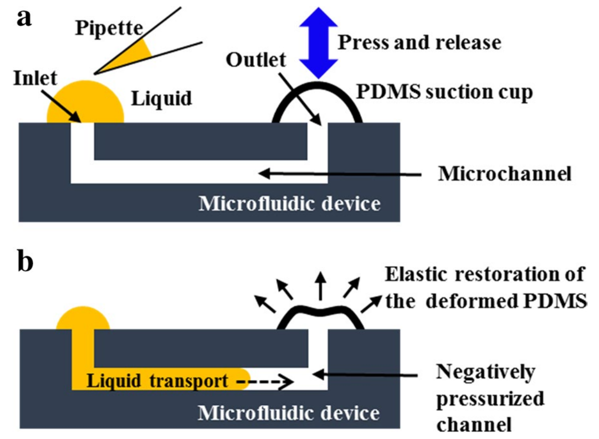

Fig. 2 Operation mechanism of the PDMS suction cup. **a** A user places the PDMS suction cup at the outlet of the device and presses it to deform, which negatively pressurizes the channel. **b** Liquid is continuously pumped through the channel by the elastic restoration of the deformed PDMS suction cup

Finger-triggered equipment-free fluid pumping

To drive the fluid, the user places the cup at the outlet of the microfluidic device, dispenses the fluid at the inlet, and then presses-and-releases the cup with a finger (Fig. 2a). This procedure creates negative pressure in the microfluidic device, and the fluid is delivered continuously through the microchannel by elastic restoration of the deformed PDMS suction cup (Fig. 2b). Figure 3 shows the entire process of the PDMS suction cup operation for the finger-triggered fluid driving in the microfluidic device. During the operation, the suction cup can be fixed to the device with no leakage (i.e., tight sealing, in which no air leakage occurred between the cup and the device) without using any adhesives, thereby allowing a simple and reversible integration of the cup to the device and requiring no pre-treatment (e.g., pre-degassing). Furthermore, the pumping performance of the suction cup can be adjusted by varying the cup geometry or fabrication conditions.

Results and discussion

Effect of cup diameter, thickness, and mixing ratio of PDMS on the pumping performance

The pumping performance was mainly dependent on the restoration force of the deformed PDMS suction cup. The restoration force varied with the cup diameter, cup thickness, and mixing ratio of PDMS (base/curing agent). The effect of these parameters on the pumping performance was investigated using a microfluidic device with a single straight channel (width: 100 μm; height: 50 μm; and length: 40 mm). The flow rate was measured using a commercial liquid flowmeter (SLI-0430, Sensirion). The initial flow rate increased as the cup diameter decreased. However, a trade-off was observed between the flow rate and the pumping duration: that is, the higher flow rates

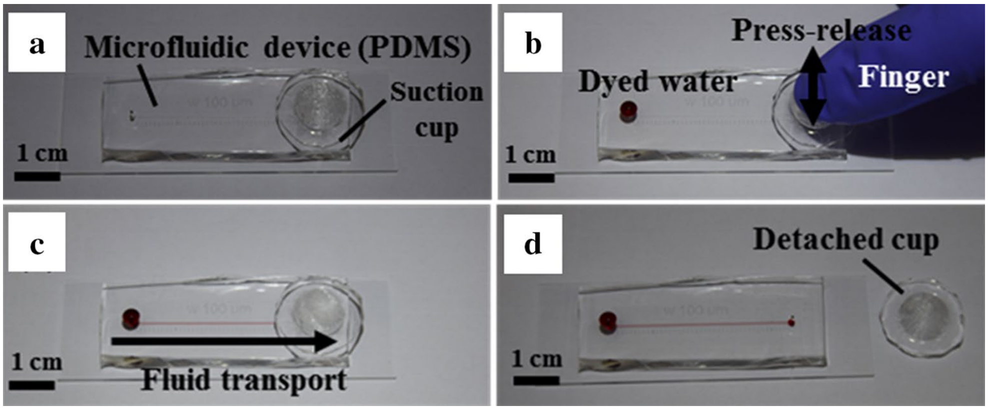

Fig. 3 Suction cup-driven equipment-free fluid pumping. **a**–**d** Finger-triggered pumping and reversible integration of the PDMS suction cup to the microfluidic device

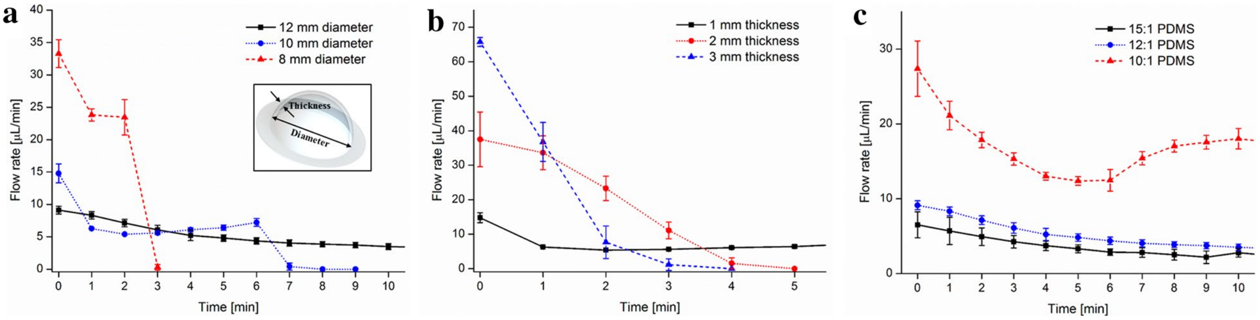

Fig. 4 Effect of the PDMS suction cup geometry and fabrication conditions on the pumping performance. **a** Effect of diameter (thickness: 1 mm; 12:1 PDMS), **b** thickness (diameter: 10 mm; 12:1 PDMS), and **c** mixing ratio (base/curing agent) of PDMS (diameter: 12 mm; thickness: 1 mm). All measurements are performed in triplicate

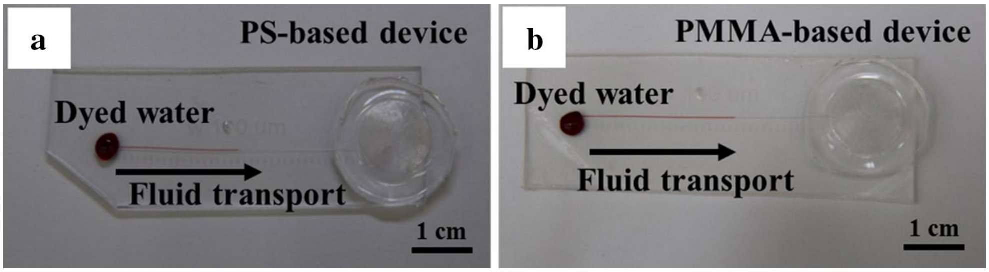

Fig. 5 Application of the PDMS suction cup for the equipment-free pumping of the thermoplastic-based microfluidic devices. A finger-triggered pumping is successfully performed. **a** Polystyrene (PS)-based device. **b** Poly(methylmethacrylate) (PMMA)-based device

decayed faster and lasted for a shorter time (Fig. 4a). The thicker cups generated a higher flow and showed a similar trade-off between the flow rate and the pumping duration (Fig. 4b). An increased PDMS mixing ratio generated a lower flow rate (Fig. 4c) as it made the cup more flexible and weakened the restoration forces of the deformed cup.

Application for thermoplastic microfluidic devices and generation of water-in-oil droplets

The PDMS suction cup can be utilized for flow generation in various material-based microfluidic devices (e.g., thermoplastic-based devices) because the suction cup can be attached to various material surfaces and does not require any pre-treatment for operation. We performed equipment-free pumping for the thermoplastic-based microfluidic devices. We prepared two types of thermoplastic microfluidic devices, namely PS and PMMA. The PDMS suction cup also operated well for the fluid flow generation in the thermoplastic-based microfluidic devices (Fig. 5). We also demonstrated the water-in-oil droplet generation using the PDMS suction cup. The droplets were generated from the microfluidic device with a flow-focusing geometry using two immiscible liquids (i.e., dyed deionized water and mineral oil containing 5% w/w Span80) (Fig. 6). Microscopic images were acquired using an inverted microscope (IX 73, Olympus) with a charge-coupled device (CCD) camera (DP80, Olympus).

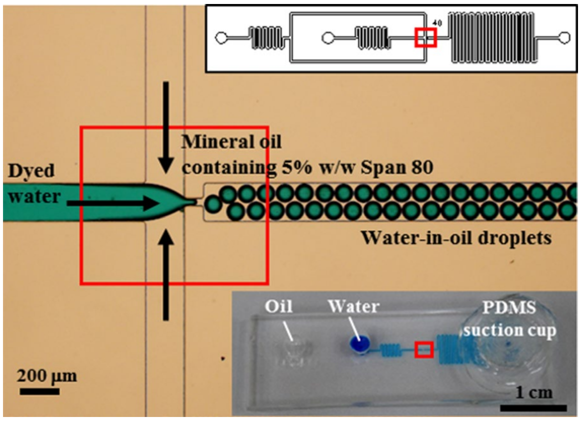

Fig. 6 Demonstration of the droplet generation. The water-in-oil droplets are continuously generated by pumping the fluids with the PDMS suction cup. The insets show the device geometry and snapshot of the integrated microfluidic device

Conclusion

This study presented a finger-triggered portable PDMS suction cup that facilitated equipment-free microfluidic pumping. A negative pressure-driven fluid flow can be generated by a simple finger-triggered operation. The effect of the diameter, thickness, and PDMS mixing ratio of the PDMS suction cup on the pumping performance was investigated. The pumping performance (i.e., pumping pressure and duration time) mainly depended on the restoration force of the deformed PDMS cup, and a trade-off existed between the pumping pressure and the duration time. Equipment-free pumping of thermoplastic-based devices and water-in-oil droplet generation were demonstrated for practical applications. We believe that this pumping method can be extensively utilized for point-of-care diagnostics or resource-limited applications.

Authors' contributions

LS performed the experiments, analyzed the data, and wrote the manuscript. KH supported the data analysis. LW performed the device fabrication. KJ supervised the research and reviewed the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Ethics approval and consent to participate

Not applicable.

Funding

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. NRF-2017R1A2B4003328) and National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2017R1C1B1008045).

Publisher's Note

Received: 2 January 2018 Accepted: 1 March 2018

References

1. Dimov IK, Basabe-Desmonts L, Garcia-Cordero JL, Ross BM, Ricco AJ, Lee LP (2011) Stand-alone self-powered integrated microfluidic blood analysis system (SIMBAS). Lab Chip 11:845–850
2. Kim H, Lee S, Lee W, Kim J (2017) High-density microfluidic particle-cluster-array device for parallel and dynamic study of interaction between engineered particles. Adv Mater 29:1701351
3. Tan WH, Takeuchi S (2007) A trap-and-release integrated microfluidic system for dynamic microarray applications. PNAS 104:1146–1151
4. Kim H, Kim J (2014) A microfluidic-based dynamic microarray system with single-layer pneumatic valves for immobilization and selective retrieval of single microbeads. Microfluid Nanofluid 16:623–633
5. Chung K, Rivet CA, Kemp ML, Lu H (2011) Imaging single-cell signaling dynamics with a deterministic high-density single-cell trap array. Anal Chem 83:7044–7052
6. Lin CH, Hsiao YH, Chang HC, Yeh CF, He CK, Salm EM, Chen C, Chiu IM, Hsu CH (2015) A microfluidic dual-well device for high-throughput single-cell capture and culture. Lab Chip 15:2928–2938
7. Kim H, Lee S, Lee J, Kim J (2015) Integration of a microfluidic chip with a size-based cell bandpass filter for reliable isolation of single cells. Lab Chip 15:4128–4132
8. Inman W, Domansky K, Serdy J, Owens B, Trumper D, Griffith LG (2007) Design, modeling and fabrication of a constant flow pneumatic micropump. J Micromech Microeng 17:891–899
9. Adde-Mensah KA, Cheung YK, Fekete V, Rendely MS, Sia SK (2010) Actuation of elastomeric microvalves in point-of-care settings using handheld, battery-powered instrumentation. Lab Chip 10:1618–1622
10. Zimmerman M, Schmid H, Hunziker P, Delamarche E (2007) Capillary pumps for autonomous capillary systems. Lab Chip 7:119–125
11. Gervais L, Delamarche E (2009) Toward one-step point-of-care immunodiagnostics using capillary-driven microfluidics and PDMS substrates. Lab Chip 9:3330–3337
12. Safavieh R, Juncker D (2013) Capillarics: pre-programmed, self-powered microfluidic circuits built from capillary elements. Lab Chip 13:4180–4189
13. Qin L, Vermesh O, Shi Q, Heath JR (2009) Self-powered microfluidic chips for multiplexed protein assays from whole Blood. Lab Chip 9:2016–2020
14. Liang DY, Tentori AM, Dimov IK, Lee LP (2011) Systematic characterization of degas-driven flow for poly(dimethylsiloxane) microfluidic devices. Biomicrofluidics 5:024108. https://doi.org/10.1063/1.3584003
15. Li G, Luo Y, Chen Q, Liao L, Zhao J (2012) A "place n play" modular pump for portable microfluidic applications. Biomicrofluidics 6:014118. https://doi.org/10.1063/1.3692770
16. Begolo S, Zhukov DV, Selck DA, Li L, Ismagilov RF (2014) The pumping lid: investigating multi-material 3D printing for equipment-free, programmable generation of positive and negative pressures for microfluidic applications. Lab Chip 14:4616–4628
17. Zimmerman M, Bentley S, Schmid H, Hunziker P, Delamarche E (2005) Continuous flow in open microfluidics using controlled evaporation. Lab Chip 5:1355–1359
18. Nie C, Frijns AJH, Mandamparambil R, den Toonder JMJ (2015) A microfluidic device based on an evaporation-driven micropump. Biomed Microdevices 17:47. https://doi.org/10.1007/s10544-015-9948-7
19. Iwai K, Shih KC, Lin X, Brubaker TA, Sochol RD, Lin L (2014) Finger-powered microfluidic systems using multilayer soft lithography and injection molding processes. Lab Chip 14:3790–3799
20. Iwai K, Sochol RD, Lee LP, Lin L (2011) Finger-powered bead-in-droplet microfluidic system for point-of-care diagnostics. Paper presented at the 25th international conference on micro electro mechanical systems, Paris, France, 29 January–2 February 2012
21. Li W, Chen T, Chen Z, Fei P, Yu Z, Pang Y, Huang Y (2012) Squeeze-chip: a finger-controlled microfluidic flow network device and its application to biochemical assays. Lab Chip 12:1587–1590
22. Qiu X, Thompson JA, Chen Z, Liu C, Chen D, Ramprasad S, Mauk MG, Ongagna S, Barber C, Abrams WR, Malamud D, Corstjens PLAM, Bau HH (2009) Finger-actuated, self-contained immunoassay cassettes. Biomed Microdevices 11:1175. https://doi.org/10.1007/s10544-009-9334-4