Supplementary Material (ESI) for Lab on a Chip

A Disposable Planar Peristaltic Pump for Lab on a Chip

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1. Movie Clips

Movie files "clip1" and "clip2" show capabilities of the pump for self priming and reversing flow direction, respectively. The movies play at a double speed while showing the pump from above. Dyed water is being pumped by revolving three identical Ø8 mm ball bearings at 6 rpm clockwise (clip 1) or counter-clockwise (clip 2). Clip 1 also shows the pump being capable of driving air bubbles out.

2. Pump prototyping

The pump prototype was realized by permanently bonding a pair of PDMS sheets (Sylgard 184, Dow Corning) made through soft lithography. The layout is shown in Fig. S-1.

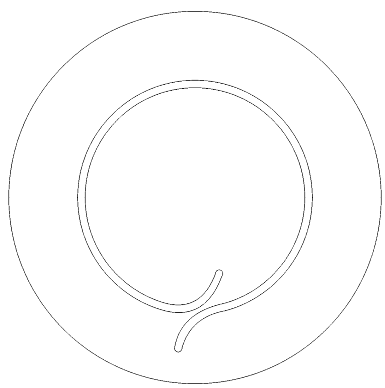


Figure S-1: Mask layout of the pump design. The channel width is 2 mm and the midpoint of the channel is located 30 mm from the loop centre.

The top sheet (350 µm thick) contained the fluidic channel 2 mm wide and 100 µm deep replica-moulded from a pattern of SU-8 (MicroChem). The section of the sheet backing the channel was 250 µm thick. The bottom sheet (450 µm thick) was a plain layer of PDMS. Thickness of each sheet was controlled by limiting the weight of degassed PDMS mixture (base:curing agent at a ratio of 10:1 by weight) poured into a confined region of 8-inch silicon or glass wafers: 5 grams poured into an SU-8 patterned area of Ø10 cm for the top sheet and 6 grams poured into a plain area of Ø12 cm for the bottom sheet. Both wafers were further kept under vacuum to degass bubbles. On the top sheet while uncured, two pre-moulded PDMS cubes (5 mm) were placed at the inlet/outlet coordinates for structural reinforcement of the fluidic interconnects. After having been completely cured in an oven at 80 °C for 2 hours, the top sheet was peeled off the wafer substrate and then punched with inlet/outlet holes with diameter 0.5 mm. The top sheet was placed upon the bottom sheet which was partially cured at 80 °C for 10 min and both were allowed to permanently bond together by further curing at 80 °C for 2 hours. The pump was peeled off the wafer and then transferred onto a poly(methyl methacrylate) (PMMA) substrate that was 1 mm thick. Throughout the process, a spirit level was used to ensure a leveled surface to achieve a uniform sheet thickness.

3. Portable System

Rare-earth magnets, neodymium ($Nd_2Fe_{14}B$), were retrieved from failed hard-disk drives and stripped off their shields. Three identical such magnets were symmetrically positioned off-centered ~120º apart on an aluminum disk 10 mm diameter. The magnets were clamped in place by counter magnets located on the opposite side of the disk. This way of clamping was strong enough to keep the magnets in place at high spin rates (<600 rpm) but allowed for their manipulation on the disk when a sufficiently large force applied during alignment. The disk was then mounted on the shaft of a DC motor equipped with a gear box (2342S012CR, Faulhaber) and driven by a microcontroller (MCDC 3006S, Faulhaber). The PMMA substrate supporting the planar pump was placed on four identical posts fencing the disk and ensured a minimal separation (<1 mm) between the substrate and the revolving magnets. Location of each magnet was adjusted such that a stainless-steel ball bearing (AEC, Singapore) on the planar pump attracted by the magnet can coincide with the circular channel layout while rolling and tracing the path of the revolving magnet.

4. Characterization

The pump prototype has been characterized by utilizing the experimental set-up described in Fig. S-2. A tubing connected to the inlet of the pump was immersed in a beaker of water kept on a balance (B200-C, Fisher Scientific) whereas a tubing from the pump outlet was connected to a water column. To apply a back pressure on the pump, the level of water in the column was accordingly adjusted with respect to that on the balance. The weight of water being pumped in a given time interval was determined by a differential reading on the balance and converted into volumetric flow rate using density of water 1 g/cm^3. For every experimental condition (e.g. fixed back pressure and pump rate), a set of five differential readings were taken on the balance, each collected after a two-minute interval. Mean and standard deviation values of each set of readings were presented in plots.

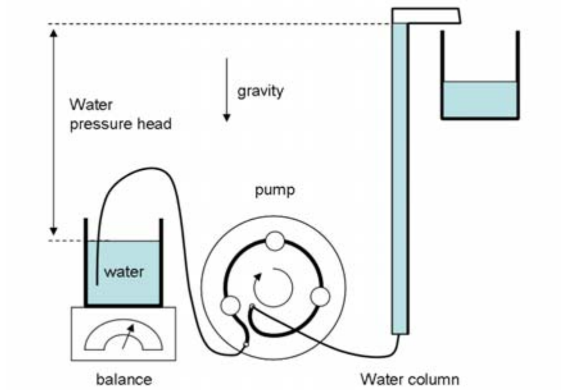
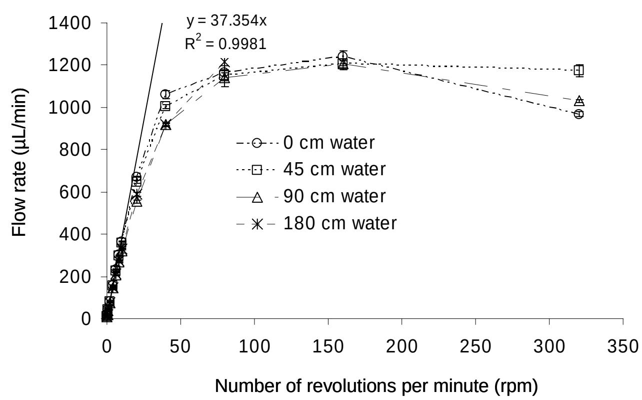


Figure S-2: Diagram of the experimental setup used for characterizing the planar pump

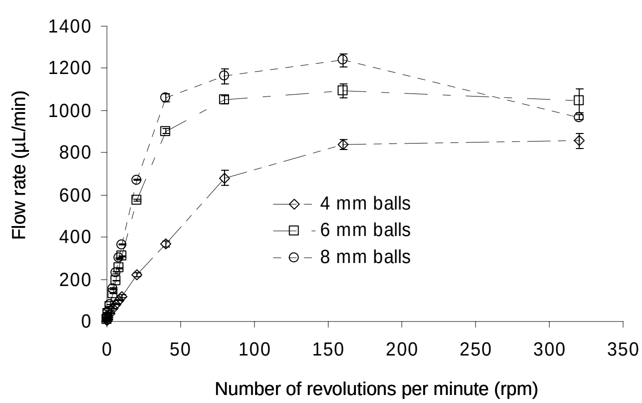
5. Results

This section includes full-scale version of the pump characteristics (Fig. S-3) presented in the main text (Fig. 3). It also includes additional plots showing the effect of number of balls on the flow rate (Fig. S-4) and the repeatability of flow rates between two identical pumps (Fig. S-5).

(a)



(b)



(c)

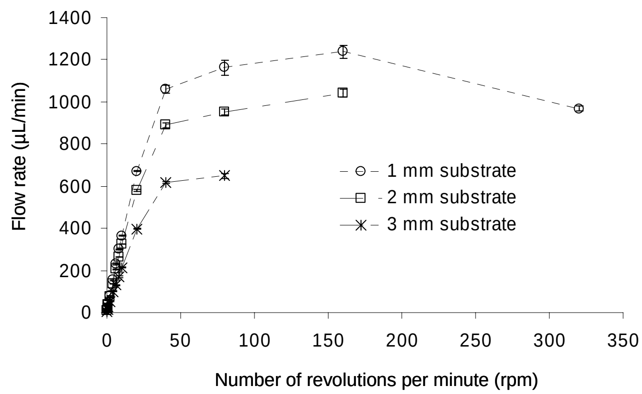
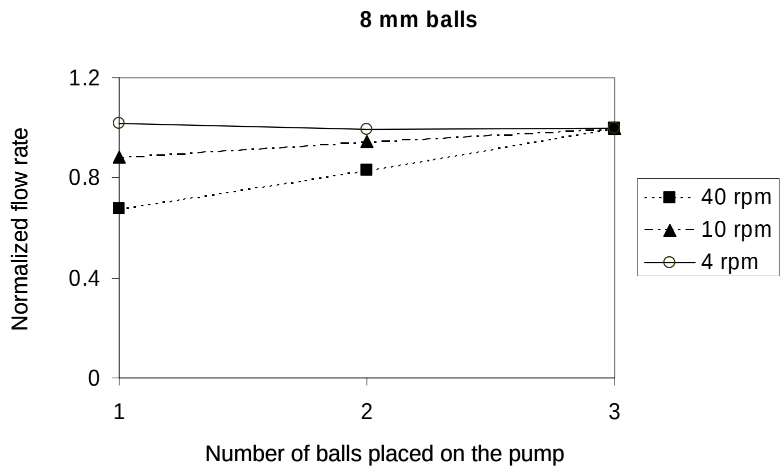
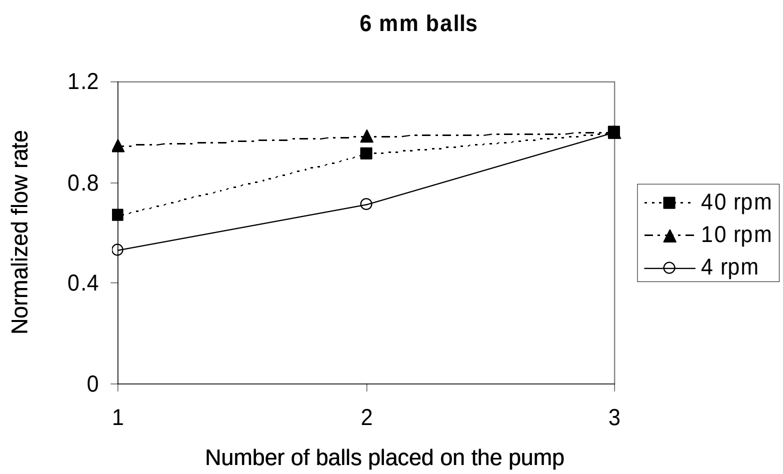


Figure S-3 The pump characteristics (8-mm bearings, 1-mm substrate, and minimal back pressure unless otherwise stated) at various levels of: (a) back pressure; (b) ball bearing size; and (c) PMMA substrate thickness. All the data were derived from the same PDMS pump.

(a)



(b)



(c)

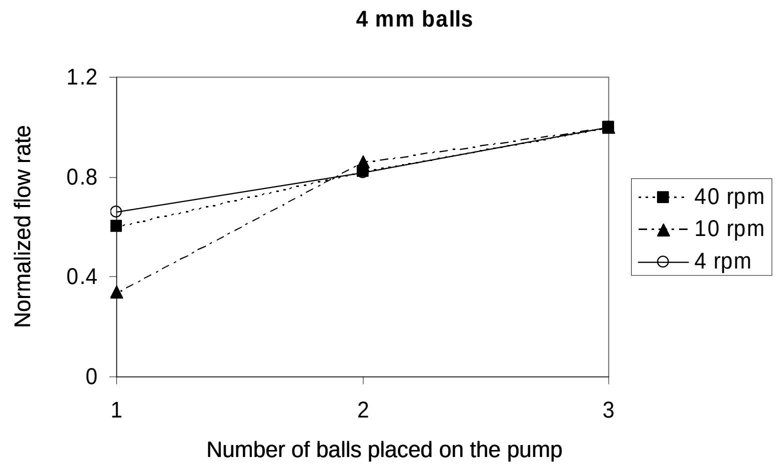


Figure S-4 Normalized flow rate versus count of ball bearings kept on the pump (1-mm thick substrate and minimal back pressure) for (a) 8 mm; (b) 6 mm; and (c) 4 mm ball bearings at three different settings of the pump cycle (legend). All the flow rates were normalized with respect to that obtained with three ball bearings from the corresponding set. The results indicate that the flow rate considerably increases with the number of ball bearings kept on the pump with the exception of 8-mm bearings at 4 rpm and 6-mm bearings at 10 rpm.

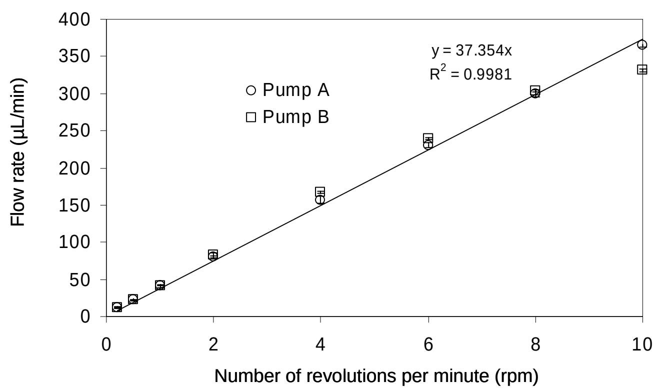


Figure S-5 The pump characteristics (8-mm bearings, 1-mm substrate, and minimal back pressure) obtained from two identical pumps. The flow rates are in good agreement at lower pump cycles (below 10rpm) where they are relevant to typical microfluidic applications. They may not fully agree at larger pump cycles probably due to pronounced effect of slight inaccuracies in their alignment.

6. Summary

A unique feature of the pump is the use of readily-available stainless-steel ball bearings coupled with rotating/translating rare-earth magnets as *reconfigurable* actuating elements on soft-state microfluidic devices. These actuators are reusable since they do not come in contact with the liquid and preserve a simple (low-cost) device structure (fabrication). They work by delivering localized compressive forces from exterior and hence need only a close physical contact with the device, eliminating any external wiring or plumbing to the device. This is unlike of many existing integrated micropumps. Moreover, the ball-bearings, immobilized on the channels, can act as magnetic valves which do not require any power to maintain their on or off state. It may be possible to further scale down the pump by employing smaller ball bearings and magnets. This may require reducing the pump and substrate thickness to minimize the loss of effectiveness due to scaling. Nevertheless, even at the scales shown here, we believe that the pump can be integrated around microfluidic devices without considerably increasing their overall size since these devices typically measure in the order of centimeters.

The new pump offers several advantages over alternative techniques whereby microfluidics can be set free from external tubing and wiring. Unlike compact discs (CDs) based on the centrifuge-driven microfluidics, the pump does not have to spin and hence requires neither mechanical balancing nor sophisticated optics for flow imaging.[3] The pump can be made more compact than a CD which typically increases in size with the fluidic layout expanding out to harness centrifugal forces. The pump can also be made to reverse the flow direction (see movie clip2). As compared to Braille-driven microfluidics which usually limits the actuation by the Braille standards, the pump can deliver a wide range of flow rates by utilizing various sizes of ball bearings and magnets.[11]