Supplementary Information

A self-priming, roller-free, miniature, peristaltic pump operable with a single, reciprocating actuator

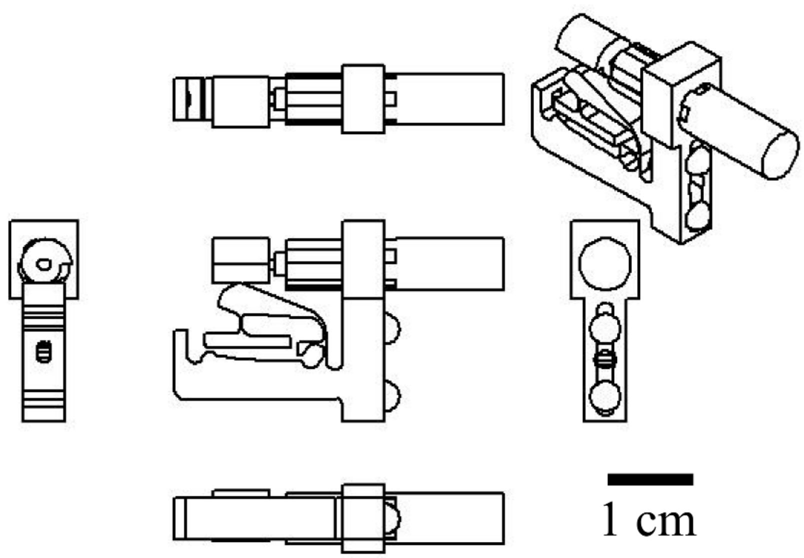
Viktor Shkolnikov[a], John Ramunas[b], Juan G. Santiago[a]*

[a] *Department of Mechanical Engineering,* [b] *Department of Neuroscience, Stanford University, Stanford, CA 94305, USA. *Tel: 650-723-7657; Fax: 650-723-5689; E-mail: juan.santiago@stanford.edu*

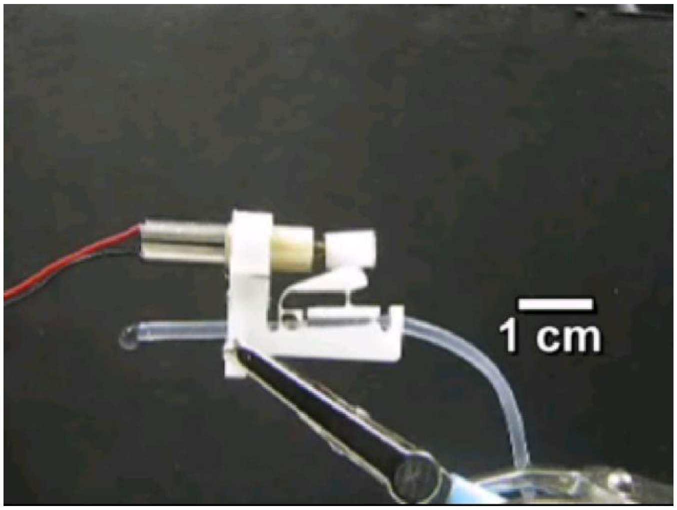
We here present drawings, images, and videos of motor, shape memory alloy wire, and manually actuated versions of the peristaltic pump. The drawings are to scale and show multiple views of the assembled pump with actuator (for the versions actuated by motor and SMA wire), but without tubing. The videos show the pump operating at nominal voltage, with minimal back pressure, pumping deionized water at ~ 22^{o}C.

We here also discuss our motor selection procedure, present a detailed schematic of the pumping cycle of the motor actuated pump, including a schematic of the cam operation, and present data for actuation frequency (motor speed) as a function of driving voltage. Figures S.1 through S.5 present drawings, movies and images of the three pump designs.

Motor actuated version of the peristaltic pump

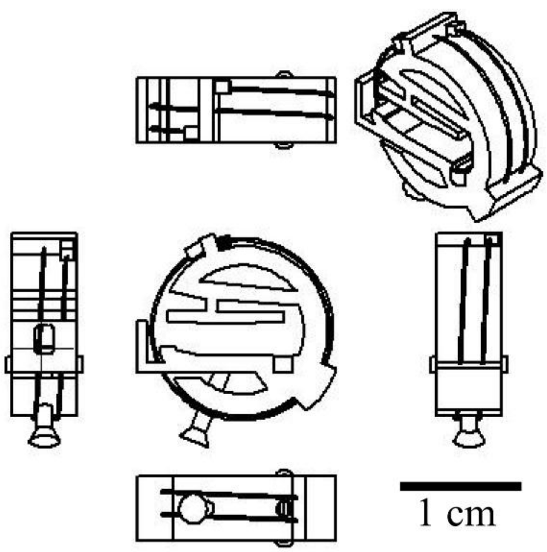


S1. Front, left, top, right, bottom and isometric views of the motor actuated version of the peristaltic pump. Drawings to scale.

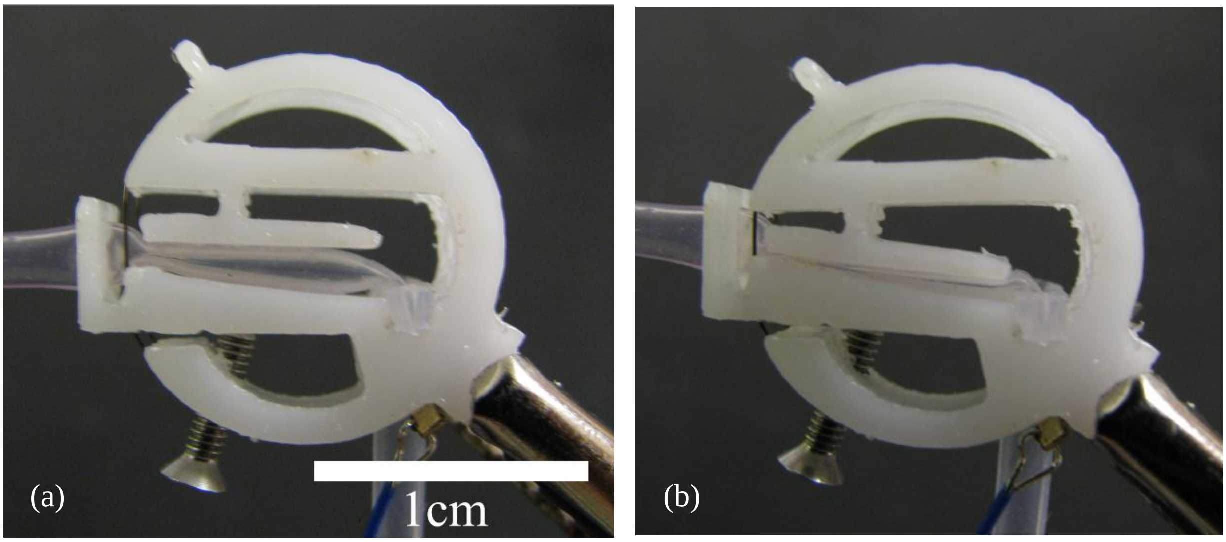


S2. Video of the motor actuated version of the peristaltic pump (video uploaded as a separate file). This pump operates at 3 V, with minimal back pressure, pumping deionized water. Figures of merit for the pump: operating voltage, 1.75 – 3 V; flow rate range, 0 – 780 µl/min; operating pressure 0 – 48 kPa; power consumption, 40 – 90 mW; weight, 3.6 g; package volume 6.2 cm^3.

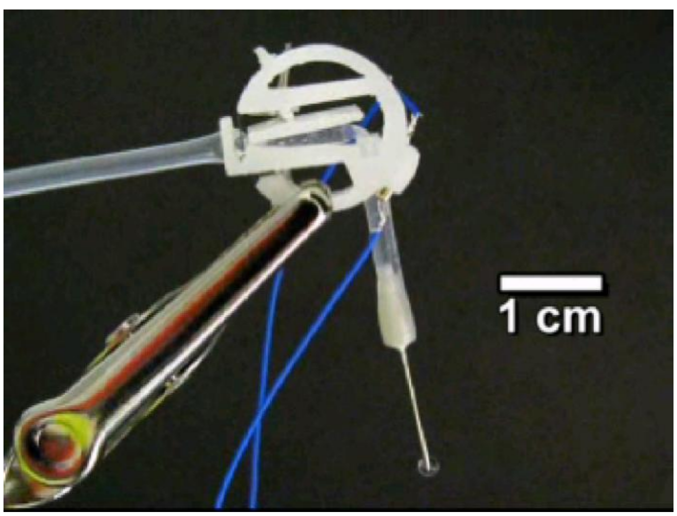
Shape memory alloy (SMA) wire actuated version of the peristaltic pump



S3. Front, left, top, right, bottom and isometric views the shape memory alloy (SMA) wire actuated version of the peristaltic pump. SMA wire is shown wrapped around the pump body. A tensioning screw tensions the SMA wire around the body. Drawings to scale.

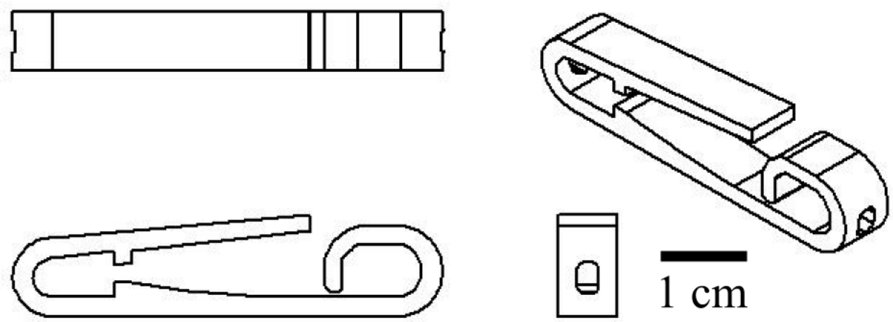


S4. (a) The SMA wire is relaxed (stretched): the upstream valve and pump chamber are both open and the pumping chamber refills from the upstream. (b) The SMA wire is contracted (electrical current is applied to the wire): the plunger closes the upstream valve and compresses the pumping chamber, raising the pressure within. This opens the downstream burst valve, and expels the fluid.

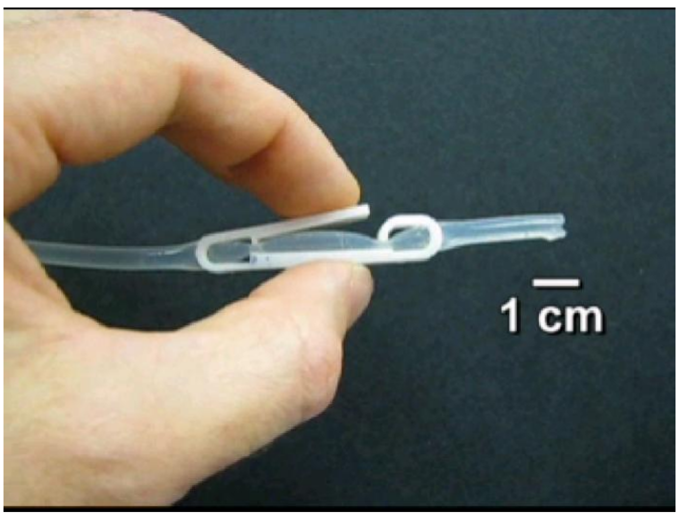


S5. Video of the SMA wire actuated version of the peristaltic pump (video uploaded as a separate file). This pump operates at 4 V, with minimal back pressure, pumping deionized water. Figures of merit for the pump: operating voltage, 4 V; flow rate range, 0 – 60 μl/min; operating pressure, 0 – 69 kPa; power consumption, 420 mW; weight, 0.9 g; package volume 1.3 cm^3.

Manually actuated version of the peristaltic pump



S6. Front, top, right, and isometric views (to scale) of the manually actuated version of the peristaltic pump. Drawings to scale.



S7. Video of the manually actuated version of the peristaltic pump (video uploaded as a separate file). The pump is actuated by hand at several speeds and pumps deionized water with minimal back pressure. Faster actuation leads to larger flow rates. The pump weighs 2.6 g, and has a package volume of 4.2 cm^3.

Discussion of motor selection

Our criteria for motor selection were dictated in part by the original intended application of our pump, which was a miniaturized drug delivery device for small animals. The criteria we used for our motor selection were as follows.

<u>Required:</u>

- Small size

- Torque of at least 10 mN·m which is twice the maximum torque required to drive the pump using a cam of ~4.5 mm radius, which was our desired radius as this makes the cam the same diameter as the pump thickness
- Rotation speed slightly less than the maximum cycle speed of the pump, at rated voltage

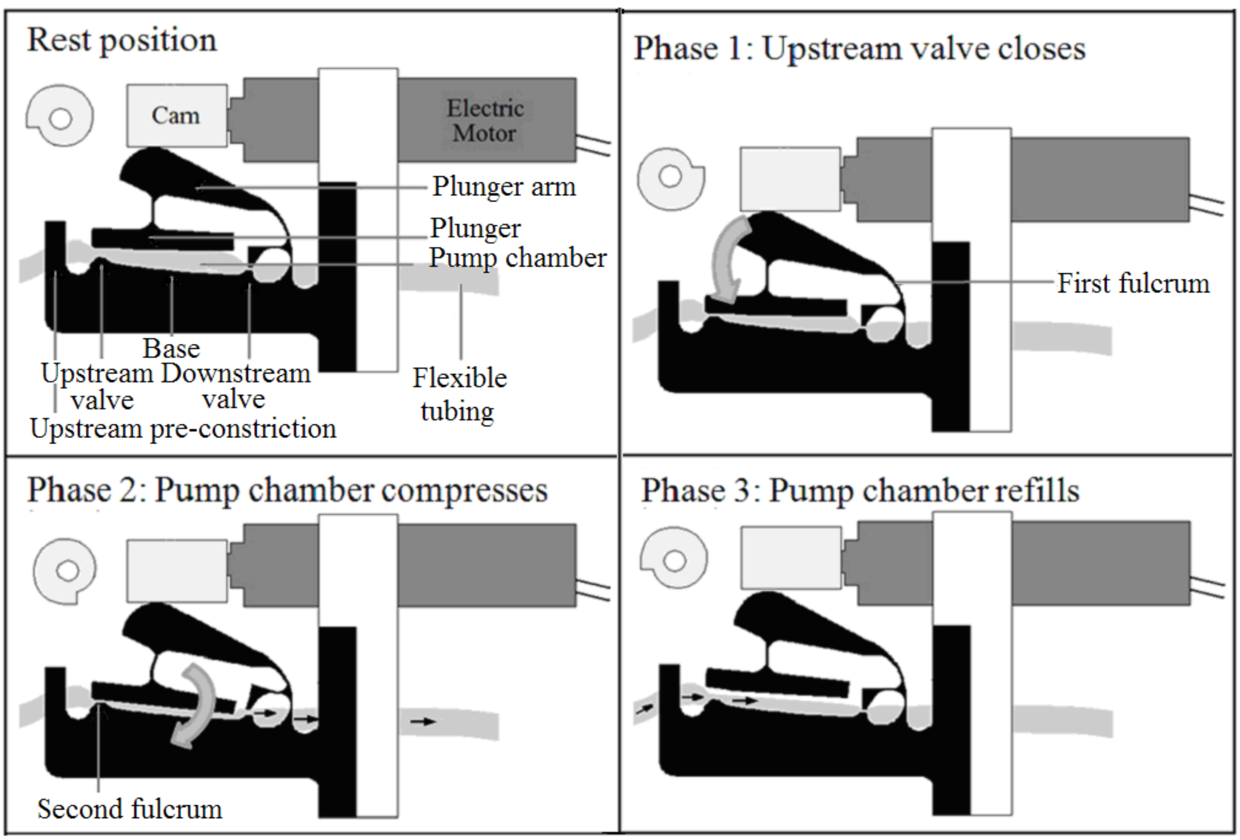
<u>Desired:</u>

- Long rated motor half-life under lateral loading of 300 grams-force
- Maximum 4 V rated voltage (to make the pump compatible with a single Li-ion battery)
- Low current consumption
- Provision on motor for convenient mounting of motor to pump
- Metal D-shaped shaft to prevent cam slippage
- Low cost (since ideally the pump could be used in disposable applications)

We considered several motors, including the higher performance motors (e.g. from MicroMo Electronics, Inc), and piezo "squiggle" motors (New Scale Technologies, Inc), and decided that the motors from gizmoszone.com met our criteria well: these motors are small in size and weight, produce 11.8 mN·m torque, rotate at 200 RPM while operating below 4 V, and are also inexpensive (<$20).

Detailed schematic of the pump cycle for the motor-driven pump

Figure S8 shows schematics of the pumping operation. In the top left of each drawing, we show end-views of the cam. The cam should be large enough to allow travel of the plunger arm for sufficient stroke volume, but overly large cams require excessive torque and stall the motor. The difference between the major and minor radii of the cam is proportional to the distance the plunger arm depresses and so is proportional to stroke volume. The cam boundary shape is such as to give a steady depression of the plunger arm through approximately 360^o of motion (Phase 1 and 2) and then give an abrupt return of the plunger arm to its initial position (Phase 3). An abrupt return is necessary to allow the upstream valve to open before the pumping chamber and thus draw fluid into the pumping chamber. If the pumping chamber were to open before the upstream valve, the pumping chamber would attempt to draw fluid from downstream as well as upstream valve; and this would thus decrease the amount of fluid pumped downstream per stroke.

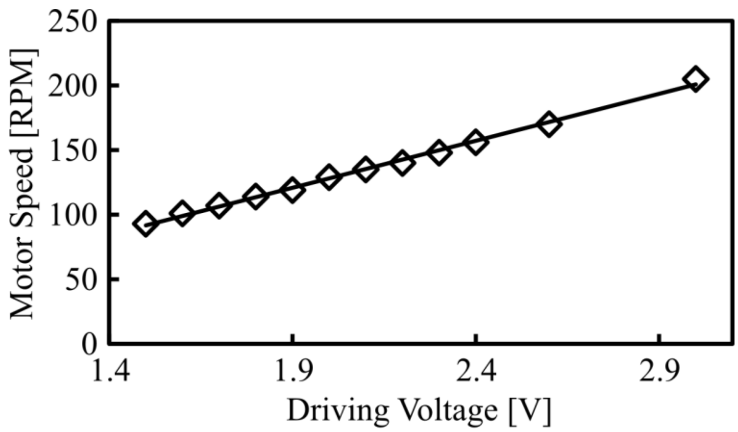


S8. Detailed schematic showing phases of the pumping cycle. Black arrows indicate flow direction. Phase 1: Cam rotation pushes down on the plunger arm, pinching tubing and creating upstream valve. Phase 2: Further motion of the plunger arm rotates the plunger clockwise (about the protrusion of the upstream valve), compressing the pumping chamber. Increased pressure in the pumping chamber causes the downstream burst valve to open, expelling fluid from the pumping chamber. Phase 3: The downstream valve closes as pressure is reduced in the pumping chamber. As the cam rotates further, it allows the plunger arm to spring upward, and the elasticity of the tubing and the line pressure open the upstream valve. The pumping chamber draws liquid through the now-open upstream valve into pumping chamber.

The cam was fabricated using a Roland MDX-540 CNC Milling Machine (Roland Corp., Irvine, CA) with a 1/16" diameter end mill (McMaster-Carr, Santa Fe Springs, CA). The cam contour is as follows: From its minimum value of r_{min} = 1.35 mm, the design cam radius increases linearly with increasing angle of rotation (counter-clockwise as shown in the drawing) to a maximum value of r_{max} = 2.50 mm after approximately 360^o of revolution. The step change from the maximum radius back to the minimum radius was made as abrupt as possible given our fabrication method.

Actuation frequency as a function of driving voltage

Below is a plot of actuation frequency as a function of driving voltage for the experimental conditions of Fig. 3 of the main paper. These data were obtained using the motor actuated pump version for negligible back pressure. We measured motor rotational speed using an optical non-contact tachometer (Neiko Tools USA - eToolsCity, Walnut, CA). As expected (for a motor-speed-limited and not torque-limited device) there is a linear relationship between driving voltage and motor speed.



S9. Motor speed as a function of driving voltage while pumping deionized water at 22^{o}C against minimal back pressure. As expected, motor speed (actuation frequency) increases linearly with driving voltage.