

Supporting information for
Soft, Rotating Pneumatic Actuator

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Experimental

Fabrication of the cVAMs

The cyclical vacuum-actuated machines (cVAMs) were created by replica molding (Figure S 1). We designed the molds using computer-aided design (CAD; Solidworks) and fabricated them in acrylonitrile butadiene styrene (ABS) plastic using a 3D printer (StrataSys Fortus 250mc). Three ABS parts are assembled to form the mold for the top piece. A wooden dowel is suspended in the middle of the mold to form the rod. The mold for the support slab consists of a flat bottom plastic dish. We cured a silicone-based elastomer (e.g., Ecoflex 00-30) against the molds at 60°C for 30 minutes to produce the two parts of the cVAMs. These two parts were aligned and bonded together by applying uncured elastomer at their interface, prior to placing them in an oven and curing at 60 °C for 30 minutes. Lengths of tubing (Intramedic polyethylene tubing, ID 0.76mm) for pneumatic actuation were attached to the structure through the bottom (using a needle to puncture holes). The elastomer forms a pneumatic seal around the tubing due to its elasticity.

In order to test the effect of materials on the performance of the actuator, we used either Dragonskin® 10NV, or mixtures of Dragonskin and Sylgard 184 (PDMS). We varied the elastic moduli of the fabricated elastomer in a manner similar to that of Russo *et al*¹. The elastic modulus of the mixed elastomers are approximately proportional to their volume fractions. Thus, we can estimate the moduli by the following equation:

$$E_{mix} = \frac{E_{PDMS}V_{PDMS} + E_{DragonSkin}V_{DragonSkin}}{V_{PDMS} + V_{DragonSkin}}$$

where E is the elastic modulus at 100% extension, and V is the volume of the component added. The elastic moduli of the materials used are reported in Table S1.

Actuators with varying numbers of chambers (three, four, or five) were fabricated by changing the base part of the mold before pouring the elastomers, while maintaining the outer diameter and the inner wall thickness.

The actuators with varying size scales were fabricated in Ecoflex 00-30 by changing the molds as well, where all dimensions illustrated in Figure S 1 were scaled linearly either 2x or 3x.

The body of the walker was produced using a similar technique as the single actuator; it was molded in a silicone-based elastomer (Ecoflex 00-30) against the molds consisting of several ABS 3D-printed parts. The cVAMs were attached to the body by applying uncured elastomer at their interface, prior to placing them in an oven and curing at 60 °C for 15 minutes.

Frequency characterization

Actuators were controlled by a miniature valve control system (built in-house, details below, Figure S 7), containing 12V solenoid valves (SMC) with flow conductance of 0.08 L/s/bar and response time <5ms, which were driven by the microcontroller board Arduino Due. The time resolution used to define the steps was 1 ms. As an example, the actuators with four chambers were actuated by the microcontroller by using four valves with the sequence (0001-0011-0010-0110-0100-1100-1000-1001) to advance cyclical motion: there were, thus eight steps per rotation. Each step in the sequence was kept at equal time intervals. We could change the intervals directly through a USB serial control interface from a computer (MacBook Pro). We recorded the performance of the actuator using a GoPro Hero 4 at 240 fps and 720p HD resolution. Video and images were processed and analyzed in MATLAB R2014b or National Institutes of Health ImageJ using custom-written scripts. A constant negative pressure was supplied through a centralized vacuum line in our laboratory.

Pressure and Force Characterization

We varied the supplied negative pressure (the difference between the atmospheric pressure and the pressure applied to the elastomer) over the range 0 kPa to -90 kPa using an electronic controller (Figure S 8) when no load was applied to the rod of the actuators. The angle of deflection was measured by using a DSLR camera EOS 550D with 24-mm F2.8 EF-S lens (Canon) from a front view or side view by recording a video at 50 fps (720p HD or 640x480 resolution). As before, the video and images were processed using MATLAB and ImageJ.

In order to characterize the torque exerted by the actuator, a load was applied to the actuators by hanging weights (in the form of small nuts weighing 0.49 g or 2.37 g) at the end of the rod. The two chambers on top were evacuated (Figure 2A) with varying negative pressures to actuate the rod. The angle of deflection was recorded using the DSLR camera.

Valve Controller

Design

For testing of the actuators, we have designed a simple valve control unit based on solenoid valves and microcontroller board, which was further interfaced through USB to a laptop computer (MacBook Pro) and controlled through in-house created software (MATLAB R2014b). Schematic and part list of the pneumatic control unit for valves are shown in Figure S 7 and Table S5, respectively. Microcontroller firmware written in C for Arduino DUE and computer software written in MATLAB are given below. Our general purpose valve controller has 18 individually addressable channels, however for current project we have used only 3-5 channels and firmware and computer software are specifically adjusted to this task, but could be easily changed when hardware is used in other setups.

Microcontroller firmware

This firmware allows exact timing of valve actuation (based on microcontroller timer interrupt) with 1 ms time resolution. Program runs the valves in circular fashion and it can be configured for 3, 4 (default) or 5 chamber actuators. Program receives the time delay in ms from computer and runs the sequence continuously until new command is received. For computer communication hardware appears as serial (COM) port and the time delay is sent as numeric value in text (string) format.

```
// Firmware for soft actuator control unit
// Based on Arduino DUE
// Alar Ainla, Whitesides Group, Harvard, 2016
//-----

//Valve to Arduino pin mapping array
int pin_address[18] = {37, 47, 45, 48, 50, 51, 53, 38, 39, 42, 44, 36, 46, 49, 43, 52, 40, 41};

volatile boolean ledon; //Sync pin
int FREQ_1kHz = 63; //Timer frequency It is set to be 1kHz (1ms resolution)

int period=20;
int counter=0;

//These are different rotatio sequences depending on number oc channels used
char sequence_3ch[6]={0x01, 0x03, 0x02, 0x06, 0x04, 0x05}; //3 chambers, 6 steps
char sequence_4ch[8]={0x01, 0x03, 0x02, 0x06, 0x04, 0x0C, 0x08, 0x09}; //4 chambers, 8 steps
char sequence_5ch[10]={0x01, 0x03, 0x02, 0x06, 0x04, 0x0C, 0x08, 0x18, 0x10, 0x11}; //5 ch,10 steps
char nr_ch=4; //Number of chambers, default is 4.

char stepnr=0; //This is sequence number, which shows which step is currently outputed

// --- THIS IS MAIN STEP MAKING CODE ---
void makeStep()
{
    char valvex;
    //Get the right output signal for pins depending on number of channels and stepnr
    if(nr_ch==3) // if 3 chambers
    {
        stepnr=(stepnr+1)%6;
        valvex=sequence_3ch[stepnr];
    }else
    if(nr_ch==4) //if 4 chambers
    {
        stepnr=(stepnr+1)%8;
        valvex=sequence_4ch[stepnr];
    }else //if 5 chambers
    {
        stepnr=(stepnr+1)%10;
        valvex=sequence_5ch[stepnr];
    }
    //Set pin states respectively
    if(valvex&0x01){ digitalWrite(pin_address[0], HIGH); }else{ digitalWrite(pin_address[0], LOW); }
    if(valvex&0x02){ digitalWrite(pin_address[1], HIGH); }else{ digitalWrite(pin_address[1], LOW); }
    if(valvex&0x04){ digitalWrite(pin_address[2], HIGH); }else{ digitalWrite(pin_address[2], LOW); }
    if(valvex&0x08){ digitalWrite(pin_address[3], HIGH); }else{ digitalWrite(pin_address[3], LOW); }
    if(valvex&0x10){ digitalWrite(pin_address[4], HIGH); }else{ digitalWrite(pin_address[4], LOW); }
    //Toggle the sync pin every time step is made
    digitalWrite(35, ledon = !ledon); //Actuate Sync pin, when step is made
}

// --- TIMER INTERUPT HANDLER ---
void TC3_Handler(){
    TC_GetStatus(TC1, 0); //Clear timer
    //When period is positive then actuate the steps
    if(period>0)
    {
        counter=(counter+1)%period;
        if(counter==0) makeStep(); //If period is >0 then run the cycle
    }
}
```

```

    }
}

// --- TIMER CONFIGURATOR ---
void startTimer(Tc *tc, uint32_t channel, IRQn_Type irq, uint32_t frequency){
    //Enable or disable write protect of PMC registers.
    pmc_set_writeprotect(false);
    //Enable the specified peripheral clock.
    pmc_enable_periph_clk((uint32_t)irq);
    //Configure timer and timer interrupt
    TC_Configure(tc, channel, TC_CMR_WAVE|TC_CMR_WAVSEL_UP_RC|TC_CMR_TCLKS_TIMER_CLOCK2);
    uint32_t rc = VARIANT_MCK/128/frequency;
    TC_SetRA(tc, channel, rc/2);
    TC_SetRC(tc, channel, rc);
    TC_Start(tc, channel);
    tc->TC_CHANNEL[channel].TC_IER = TC_IER_CPCS;
    tc->TC_CHANNEL[channel].TC_IDR = ~TC_IER_CPCS;
    NVIC_EnableIRQ(irq);
}

// --- SETUP ON BOOT UP ---
void setup() {
    Serial.begin(115200); //Initialize COM port connection. Baud rate 115200
    //Initialize pins for output
    for (int i = 0; i < 18; i++) {
        pinMode(pin_address[i], OUTPUT); //set pins to be outputs
        digitalWrite(pin_address[i], LOW); // initialize to low state (0)
    }
    pinMode(35, OUTPUT); //Sync pin
    //Initialize timer for 1KHz interput
    startTimer(TC1, 0, TC3_IRQn, FREQ_1kHz);
}

// --- MAIN LOOP ---
//Read instructions from COM port and execute them
//Inputs can be numerical values as text (integer, positive or negative)
//if period > 0 then it sets the step length in ms
//If period < 0 then actuation sequence is stopped
//Special values are:
// -3, which sets the actuation sequence for 3 chamber configuration
// -4, which sets the actuation sequence for 4 chamber configuration
// -5, which sets the actuation sequence for 5 chamber configuration
//All of these special commands also stop the actuation sequence

void loop() {
    String tmp;
    if(Serial.available()>0) //Check if input command has been received
    {
        NVIC_DisableIRQ(TC3_IRQn);
        tmp=Serial.readString(); //Read text value (must be number!)
        period=tmp.toInt(); //Converts to integer
        //Interprete special commands
        if(period===-3){ stepnr=0; nr_ch=3; }
        if(period===-4){ stepnr=0; nr_ch=4; }
        if(period===-5){ stepnr=0; nr_ch=5; }
        NVIC_EnableIRQ(TC3_IRQn);
    }
}

```

Computer software

This program takes the input parameter, which is the number of chambers in actuator (nr_ch) and runs the test sequence in which hardware is configured for the chamber number and time delay between steps (hold time) is switched in sequence 1s, 500ms, 200ms, 100ms, 50ms, 20ms, 10ms, 5ms. Every rotation speed is held for 10s.

```

function rhand = ValveController(nr_ch)

% This function automatically runs the controller
% Platform: MATLAB R2014b on MacOSX

```

```

% Alar Ainla, Whitesides Group, Harvard, 2016
% -----
serialport=serial('/dev/cu.usbmodem1411','BaudRate',115200);
fopen(serialport);
set(serialport,'Terminator',13);
pause(2);
speeds=[(-1)*nr_ch,1000,500,200,100,50,20,10,5,-1];
N=10;
delayt=10;
fprintf(' --- Start now --- \n');
for i=1:N
    fprintf(serialport,'%d\n',speeds(i));
    fprintf('Now: %d ms\n',speeds(i));
    pause(delayt);
end
fclose(serialport);
delete(serialport);
fprintf(' --- DONE! --- \n');
end

```

Computer-controlled negative pressure regulator

Design

For characterizing the performance of actuators, we have designed a computer controllable vacuum source, which was interfaced through USB to a laptop computer (MacBook Pro) and controlled through in-house created software in MATLAB R2014b. Central component of the design is electronic vacuum regulator, which adjusts the vacuum level proportionally to analog control signal (Voltage: 0 to +10V). Control signal is generated using microcontroller PWM output (3.3V, 1kHz and 8-bit resolution), RC low-pass filter (time constant $R1 \cdot C1 = 120$ ms) and operational amplifier (with 0 and 12 V rails) to match the voltage levels of the microcontroller and the vacuum regulator (from 3.3 V to 10 V). Schematic and part list of the pneumatic control unit and shown in Figure S 8 and Table S6, respectively. Microcontroller firmware written in C for Arduino DUE and computer software written in MATLAB are given below. We calibrated the controller with pressure response of the system using high accuracy digital pressure gauge. A linear calibration curve between the digital control (from 0 to 255) and vacuum level (0 to -90 kPa) is obtained (Figure S 8B). The vacuum regulator was supplied through a central house vacuum in our laboratory (approximately -95 kPa)

Microcontroller firmware

This microcontroller firmware reads the digital control value from serial port (sent as number in text format in the range 0 to 255) and sets the PWM fill factor based on it 0 corresponds to 0V and 255 to 3.3V. Average output voltages is linearly proportional to the fill factor.

```
//This firmware is used to generate PWM for adjusting vacuum regulator
//ITV0090-3UBL, which has 10V input voltage regulator
//Alar Ainla, Whitesides Group, Harvard, 2017
//-----

//PWM frequency is 1kHz
//PWM resolution is 8 bit
int PWMpin=2;

void setup() {
  // put your setup code here, to run once:
  Serial.begin(115200); //Initialize COM port connection. Baud rate 115200
  pinMode(PWMpin,OUTPUT);
  analogWrite(PWMpin,0); //Off value
}

void loop() {
  // put your main code here, to run repeatedly:
  String tmp;
  int value; //Value should be between 0 and 255 (char)
  if(Serial.available(>0) //Check if input command has been received
  {
    tmp=Serial.readString(); //Read text value (must be number!)
    value=tmp.toInt(); //Converts to integer
    Serial.println("OK!\n");
    //Interprete special commands
    analogWrite(PWMpin,value);
  }
}
```

Computer software

This program generates the vacuum ramp. Vacuum level is increased in 10 digital units, which is corresponding to 4.1 kPa (Figure S 8B). Each level is held for 5s to equilibrate the pressure and actuator response. Pressures are ramped from 0 kPa to -90 kPa and back to 0 kPa, to check for hysteresis (Figure S 6). There are 44 steps in total. In some experiments, we only used forward ramp (first 22 steps).

```
function rhand = VacuumRegulator

% This function automatically runs the controller
% Platform: MATLAB R2014b on MacOSX
% Alar Ainla, Whitesides Group, Harvard, 2017
% -----

serialport=serial('/dev/cu.usbmodem10', 'BaudRate',115200);
fopen(serialport);

pause(2);

for i=1:22
    vac(i)=i*10;
```



```

    vac(i+22)=220-(i*10);
end
N=44;

delayt=5;
fprintf(' --- Start now --- \n');
for i=1:N
    fprintf(serialport,'%d',vac(i));
    fprintf('Code: %d Pressure (mbar): %d\n',vac(i), vac(i)*(-4.1416)+4.5652);
    pause(delayt);
end

fclose(serialport);
delete(serialport);
fprintf(' --- DONE! --- \n');
end

```

Analysis

Analytical model for estimating torque output

The actuators have trapezoid-shaped walls, which are narrower at the bottom and broader on top.

For the 1x sized actuator, the bottom and top widths are $w_1 = 1.5$ mm and $w_2 = 4.5$ mm respectively, and the height is $H = 6$ mm. If pressure p is applied to such a wall, which is attached from the bottom, the torque can be calculated as:

$$\begin{aligned}\tau &= \int_0^H y dF = p \int_0^H y dS \\ &= p \int_0^H y w(y) dy = p \int_0^H y \left(w_1 + \frac{w_2 - w_1}{H} y \right) dy = \frac{pH^2}{6} (w_1 + 2w_2)\end{aligned}$$

where F is force, y is the distance from the fixed point, p is the pressure difference between the atmosphere and inside the chamber, S is the area over which pressure is exerted,

This gives the torque to pressure ratio

$$\frac{d\tau}{dp} = \frac{H^2}{6} (w_1 + 2w_2)$$

which would scale with the third power of size and it would be 63 $\mu\text{Nm/kPa}$ for 1x actuator, 500 $\mu\text{N.m/kPa}$ for 2x, and 1.7 mN.m/kPa for 3x actuator.

A comparison of the torque estimated from this model and experimental results is given in Table S7. The estimates from the model are within 20% of those measured experimentally for

the actuators fabricated in Ecoflex and Dragonskin. The experimental results are substantially lower for the actuators fabricated with stiffer materials, most likely because these actuators do not actuate completely under atmospheric conditions.

Fluidic properties and time constants of the system

Pneumatically, our actuator is analogous to an RC circuit as illustrated in Figure S 9.

Fluidic resistances of the tube is given by:

$$R_{tube} = \frac{8\mu L}{\pi r^4}$$

where $\mu = 18.27 \mu\text{Pa}\cdot\text{s}$ is viscosity of air, $L = 50 \text{ cm}$ is length of the tube, and $r = (1/32") = 0.78 \text{ mm}$ is radius of the tube. This gives fluidic resistance $R_{tube} = 6.2 \cdot 10^7 \text{ Pa}\cdot\text{s}/\text{m}^3$.

Fluidic resistance (G is the conductance reported by the manufacturer in the datasheet) of the valve is given by manufacturer datasheet:

$$R_{valve} = \frac{1}{G} = \frac{1}{0.08\text{L}/(\text{s bar})} = 1.3 \cdot 10^9 \text{ Pa}\cdot\text{s}/\text{m}^3$$

We can see that fluidic resistance of the valve is approximately more than one order of magnitude larger compared to that of the tube and thus, we can neglect the resistance of the tube in further considerations

As a crude estimate we can assume that gas reservoirs have no compliance (i.e. volume does not change). This is only a crude assumption because chamber volume does changes with applied vacuum. Since the assumption is not completely correct, the real capacitances are larger than the ones estimated here.

With constant volume and small pressure change the estimate of capacitance, C would be

$$C = V/p$$

where V is the volume and average pressure is $p = (100 \text{ kPa} + 20 \text{ kPa})/2 = 60 \text{ kPa}$.

Time constant τ , is thus

$$\tau = RC$$

Tube volume is $V_{tube} = \pi r^2 L = 9.6 \cdot 10^{-7} \text{ m}^3$

We can see that in the case of small actuators, the volume and capacitance are mainly dominated by the tube. In the case of large actuators, the volume and capacitance are dominated by the chambers.

Stirrer characterization

The wooden dowel was replaced by a stainless steel needle (10 cm 16G). A stiff rubber ball (mass, $m = 2.4 \text{ g}$, radius $r_1 = 8 \text{ mm}$) was attached to the end of the needle. The distance between the center of the ball and the soft actuator was $r_2 = 23.5 \text{ mm}$. A solution of 2% w/v carboxymethylcellulose (CMC, MW = 250,000 kDa, DS = 1.2, Acros Organics) was prepared by dissolving the CMC in water.

A solution of fluorescein disodium salt (1 mM) was prepared in water for use as a model dye and to demonstrate mixing qualitatively. This solution was injected through the needle attached to the cVAM into a container with 150 mL water, at the rate of 10 mL/min (using a syringe pump). The cVAM was either left off or operated at 375 rpm (delay of 20 ms between each step of the revolution) while delivering the fluid. A video was recorded for both conditions of delivering fluid using a GoPro Hero 4 camera at 240 fps frame rate and 720p HD resolution.

In order to understand the oscillations of the cVAM at each step of the revolution, we use the model of a damped harmonic oscillator. While operating at a frequency of 15 rpm (delay of 500 ms between steps), the oscillations of the rubber ball in air are seen in Figure 4 D. The average frequency of these oscillations is observed to be $f_{obs} = 8.8 \text{ Hz}$ (and the angular frequency

$\omega_{\text{obs}} = 55 \text{ rad/s}$). When assuming an exponential decay ($x = e^{-\gamma t}$, where x is the displacement, γ is the damping constant, and t is the time), the damping constant is measured to be $\gamma = 14/\text{s}$. We can estimate ω_0 , the angular frequency if there was no damping using:

$$\omega_0 = \sqrt{\omega_{\text{obs}}^2 + \gamma^2} = 57 \frac{\text{rad}}{\text{s}}$$

For our system, Newton's second law can be written in angular terms as:

$$I\alpha + c\omega + \kappa\theta = 0$$

where I is the moment of inertia of the oscillator, α is the angular acceleration, c is the angular viscous damping constant, ω is the angular frequency, κ is the angular spring constant, θ is the angular displacement. The moment of inertia I can be calculated using the parallel axis theorem (and assuming that the mass of the needle is negligible):

$$I = m \left(\frac{2r_1^2}{5} + r_2^2 \right) = 1.38 \times 10^{-6} \text{ kg m}^2$$

The angular spring constant, κ can then be estimated as:

$$\kappa = I\omega_0^2 = 0.0045 \text{ N m rad}^{-1}$$

Using the observed damping coefficient γ , the angular damping constant c (in air, as a result of both air and elastomer dampening) can be calculated as:

$$c = 2\gamma I = 3.9 \times 10^{-5} \text{ N m s rad}^{-1}$$

We know that viscous drag force is given by:

$$F_{\text{drag}} = 6\pi\eta r_1 v$$

where η is the viscosity of the fluid. Using the relationships, $\tau_{\text{drag}} = F_{\text{drag}} r_2$ (since the angle between F and r_2 is 90°) and $v = \omega r_2$, we can write:

$$\tau_{\text{drag}} = 6\pi\eta r_1 r_2^2 \omega$$

Using $\tau_{\text{drag}} = c \omega$, we can estimate the values of viscous damping constant, c in different fluids using

$$c = 6\pi\eta r_1 r_2^2$$

Thus, $c_{\text{air}} = 1.7 \times 10^{-9} \text{ N.m.s.rad}^{-1}$, $c_{\text{water}} = 7.4 \times 10^{-8} \text{ N.m.s.rad}^{-1}$, $c_{\text{CMC}} = 1.9 \times 10^{-4} \text{ N.m.s.rad}^{-1}$. We notice that the constants for air and water are negligible compared to the observed constant for the elastomer and thus, these fluids do not provide any additional damping effects, whereas for the CMC solution, the damping constant is one order of magnitude higher than that of the elastomer and hence increases the damping effects. To verify, we can calculate the parameter $c^2 - 4I\kappa$, which determines the nature of solutions to Newton's second law equation listed above. For air and water, $c^2 - 4I\kappa < 0$ and for CMC $c^2 - 4I\kappa > 0$, which corresponds to underdamped and overdamped cases respectively, as confirmed by Figure 4 D, E.

The power dissipated by the rubber ball due to the work done in a viscous fluid (CMC solution) can be estimated using the following equation:

$$P = 6\pi\eta r_1 v^2 = 6\pi\eta r_1 \left(\left(\frac{dx}{dt} \right)^2 + \left(\frac{dy}{dt} \right)^2 \right)$$

where x and y are the position of the ball, and t is the time. The position was extracted from the videos using a MATLAB program. These estimates of power output were plotted in Figure 4 F for various frequencies of operation.

Estimating efficiency of actuator

As described in the main text, using the setup shown in Figure 2A, we characterized the performance of the cVAM when operating with different loads. We added the weights (with mass m) to the central rod at a distance $r = 32 \text{ mm}$. As before, we tracked the position of the rod using a MATLAB program and measured the following: i) angle of deflection of actuator under different loads (Figure S 3A), and iii) the maximum actuation angle as the load changes (Figure

2D). The torque (τ) exerted by the load is related to the angular spring constant (κ) and the angle of deflection (θ) as:

$$\tau = -\kappa\theta$$

Thus, from Figure S 3A and Table S2, for Ecoflex 00-30,

$$\kappa = -\frac{1}{\text{slope}} = -\frac{1}{-6.17 \frac{\circ}{\text{mN}\cdot\text{m}}} = 9.5 \frac{\text{mN}\cdot\text{m}}{\text{rad}}$$

This estimate of angular spring constant is about double of the estimate ($4.5 \text{ mN}\cdot\text{m}\cdot\text{rad}^{-1}$) obtained from the stirring experiment above.

Figure S 3B shows the calculated work done (W_{out}) for each actuator under different torques as obtained by multiplying the angle by the torque. At the optimal torque of about $3 \text{ mN}\cdot\text{m}$, the work done by the actuator fabricated in Ecoflex 00-30 is about $340 \mu\text{J}$.

The volume of one compartment (for the four-chamber design) of the actuator is 99 mm^3 (Table S4) and two compartments are used for actuating the rod from one end to another. The pressure difference is 90 kPa . Thus, the pressure-volume work input is:

$$W_{in} = 90 \text{ kPa} * 99 * 2 \text{ mm}^3 = 17.8 \text{ mJ}$$

We define the thermodynamic efficiency of the actuator as the ratio of useful work performed by the motion of the rod (for example, stirring liquid or lifting weight) to the total work done by gas flowing out of the actuator compartments (pressure \times volume). Thus, the thermodynamic efficiency (W_{out}/W_{in}) of the actuator is approximately 2% ($0.34 \text{ mJ}/17.8 \text{ mJ}$). Losses are due to the work done by the gas being translated into non-useful deformations of the elastomer (for example, if the actuator itself bends instead of moving the rod). The work is done over approximately 150 ms (the duration for which the rod oscillates at each step of the revolution) and thus, the power is about 2.3 mW . These values of power and efficiency are obtained from a

non-optimal actuator. As seen in Table S7, the estimated torque exerted by the actuator is comparable to theoretical value if the actuator was modeled as a spring coupled to a piston. Yet, when actuating with a load, energy losses occur due to deformation of the actuator. These losses could be minimized in future iterations by making the outer walls of the actuator thicker so that the collapse of the chambers would mostly actuate the rod.

Supplementary Tables

Force characterization

Table S1: Elastic moduli of the materials used for fabricating the actuators

Material	Elastic modulus (MPa)	Source
Ecoflex® (00-30)	0.069	Manufacturer datasheet
Dragonskin® (10 NV)	0.19	Manufacturer datasheet
PDMS (Sylgard® 184)	1.8	Russo <i>et al.</i> ¹ (2016)
PDMS:Dragnoskin (1:1)	1.0	Calculated as described above
PDMS:Dragonskin (1:3)	0.6	Calculated as described above

Table S2: Characteristics of actuators fabricated in different materials. The slope of deflection angle θ vs applied torque τ , when no vacuum is applied (Figure S3A), which is inversely proportional to the angular spring constant of the actuator κ (Figure S2). We also report the slope of maximum actuation angle φ_{max} vs applied torque τ , which is difference between no applied vacuum and maximum vacuum level (Figure 2D)

Material	Slope of deflection angle θ vs applied torque τ [$^{\circ}$ / (mN.m)]. $p = 0$	Slope of maximum actuation angle φ_{max} vs applied torque τ [$^{\circ}$ / (mN.m)], $p = -90$ kPa
Ecoflex (00-30)	6.17	2.23
Dragonskin (10 NS)	5.59	1.97
PDMS:Dragonskin (1:3)	4.12	1.49
PDMS:Dragnoskin (1:1)	3.70	0.78

Table S3: This table supplements Figure S6 and compares actuators with different numbers of chambers.

	3-chamber	4-chamber	5-chamber
Max angle 1 ch ($^{\circ}$)	6.3	8	3.4
Max angle 2 ch ($^{\circ}$)	11.5	16	6.1

Sat pressure 1 ch (mbar)	-120	-900	-200
Sat pressure 2 ch (mbar)	-200	-600	-300
Slope (°/bar) 1 ch	70.4	16.1	25.4
Slope (°/bar) 2 ch	77.3	31.7	18.5

Table S4: Estimates of time constants for various actuators

Actuator	Chamber volume (10^{-7}m^3)	Total capacitance ($10^{-11}\text{m}^3/\text{Pa}$)	Time constant (ms)
3-chamber	1.4	1.8	23
4-chamber	0.99	1.8	23
5-chamber	0.75	1.8	23
4-chamber 2x size	7.9	2.9	38
4-chamber 3x size	27	6.1	79

Table S5: Part list of the pneumatic control unit for controlling valves. All SMC components were purchased from Orange Coast Pneumatics (Yorba Lina, CA). Electronic parts were obtained from Digi-Key Corporation (Thief River Falls, MN)

Component and description	Supplier part number	Source	Quantity
IC1. Arduino DUE microcontroller board (32-bit ARM Cortex-M3 with USB)	1050-1049-ND	Digi-Key	1
Switching power supply ETSA120330UDC (CUI Inc.), 120V AC in, 12V 3.3A DC out	T1079-P5P-ND	Digi-Key	1
T1. N-CH MOSFET transistor IRLZ14. 60V 10A	IRLZ14PBF-ND	Digi-Key	18
Solenoid valve. Response time: <5ms, flow conductance: 80mL/(s*bar), electrical power 12V, <100mA.	V114A-6LOU	SMC	18
Connection wire for valve	SY100-30-4A	SMC	18
Manifold. For mounting 18 valves	VV100-S41-18-M5	SMC	1
Quick-fit connectors. For 4mm tubing with M5 thread	KQ2S04-M5A	SMC	20
Quick-fit plug for small tubing.	M-04R-2	SMC	3-5

Supply Tubing. Polyurethan, OD 4mm, ID 2mm	TUS0425B-20	SMC	Few m
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Table S6: Part list of the pneumatic control unit for regulating supplied negative pressure. All SMC components were purchased from Orange Coast Pneumatics (Yorba Lina, CA). Electronic parts were obtained from Digi-Key Corporation (Thief River Falls, MN). Digital manometer was obtained from Total Temperature Instrumentation Inc. (“Instrumart”, S. Burlington, VT)

Component and description	Supplier part number	Source	Quantity
IC1. Arduino DUE microcontroller board (32-bit ARM Cortex-M3 with USB)	1050-1049-ND	Digi-Key	1
Switching power supply SDI65-24-U (CUI Inc.), 120V AC in, 24V 2.71A DC out	102-3418-ND	Digi-Key	1
IC2. Voltage regulator (LDO) +12V, 1.5A output. LM340T12	LM340T-12-ND	Digi-Key	1
IC3. J-FET operational amplified AD820	AD820ANZ-ND	Digi-Key	1
Electronic vacuum regulator. ITV0090-3UBL. 0 to -1000mbar, +24V power, 0 to 10V control signal	ITV0090-3UBL	SMC	1
Digital Pressure Gauge (Manometer). Keller LEX1 -1to 2 bar, accuracy 0.05% FS	LEX1-2-G1/4	Instrumart	1
Supply Tubing. Polyurethane, OD 4mm, ID 2mm	TUS0425B-20	SMC	Few m

Table S7: Comparison of values obtained for torque with respect to changes in pressure using an analytical model and experimental measurements

Material	Scale	Slope (°/mNm) No vacuum	Initial response slope (°/kPa)	Experimental (µNm/kPa)	Theoretical (µNm/kPa)
Ecoflex	1	6.2	0.30	48	63
Dragonskin (DS)	1	5.6	0.24	44	63
PDMS:DS 1:3	1	4.1	0.087	21	63
PDMS:DS 1:1	1	3.7	0.060	16	63
Ecoflex	2	1.9	0.78	410	500
Ecoflex	3	0.72	0.96	1340	1700

Supplementary figures

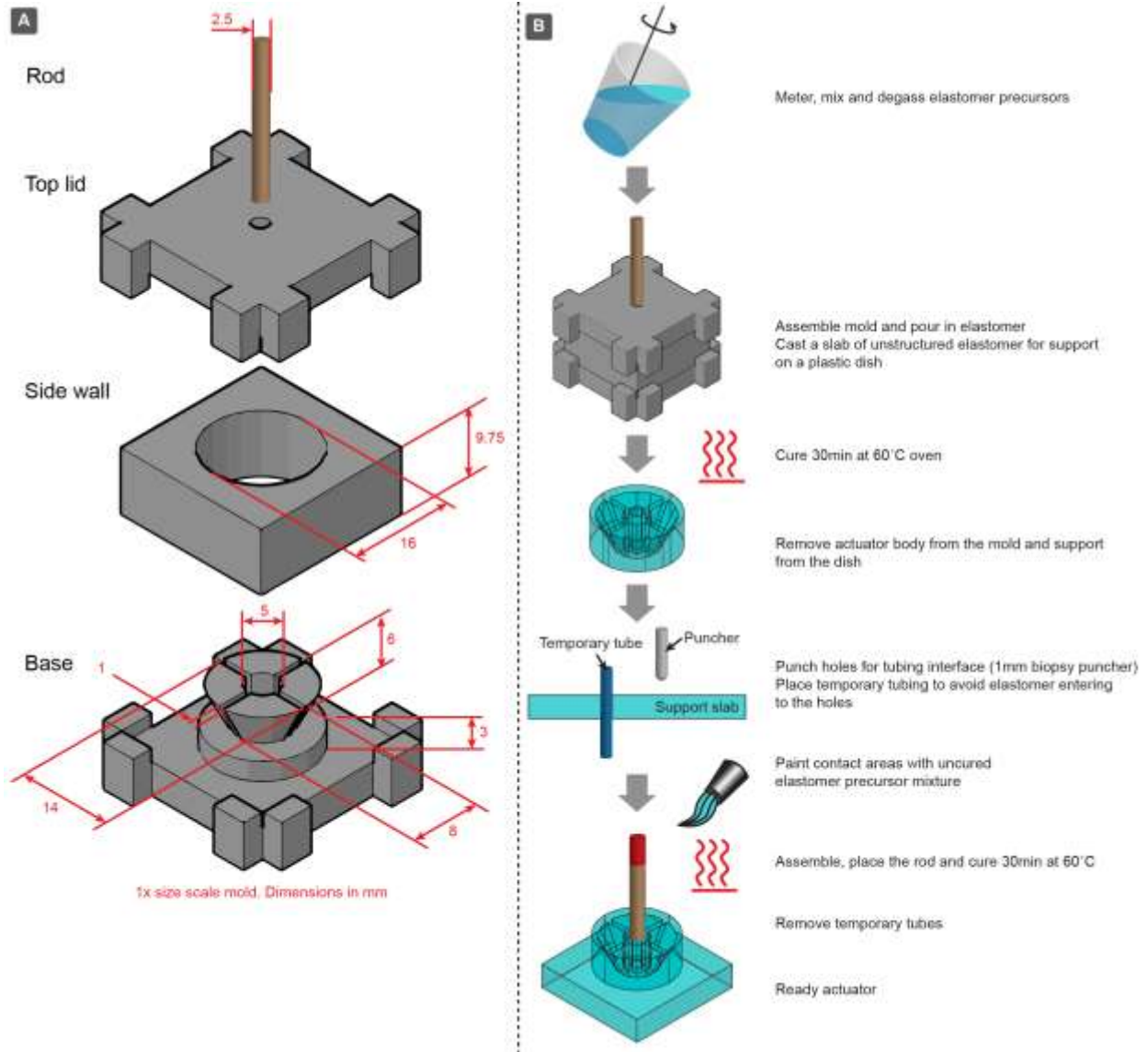


Figure S 1: Fabrication of cVAM. (A) Structure and dimensions (for the 1x model) of the mold used for making the elastomeric actuators. (B) Process of fabricating cVAMs. The actuator is fabricated by curing elastomers in a 3D-printed mold. A wooden rod suspended in the mold of the top piece is bonded into the elastomer when it cures. A support slab is prepared by pouring elastomer in a tray to obtain a thickness of about 5 mm. A sacrificial tube is placed in the support slab (by using a biopsy punch to make a hole) while the slab is being attached to the actuator

body. After the body and support slab are attached, the sacrificial tube is replaced by pneumatic tubing.

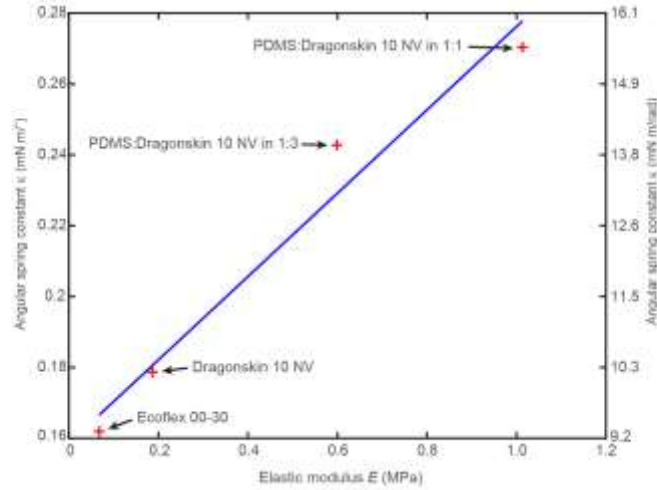


Figure S 2: Angular spring constant κ depending on elastic modulus of the material used for fabricating the actuator.

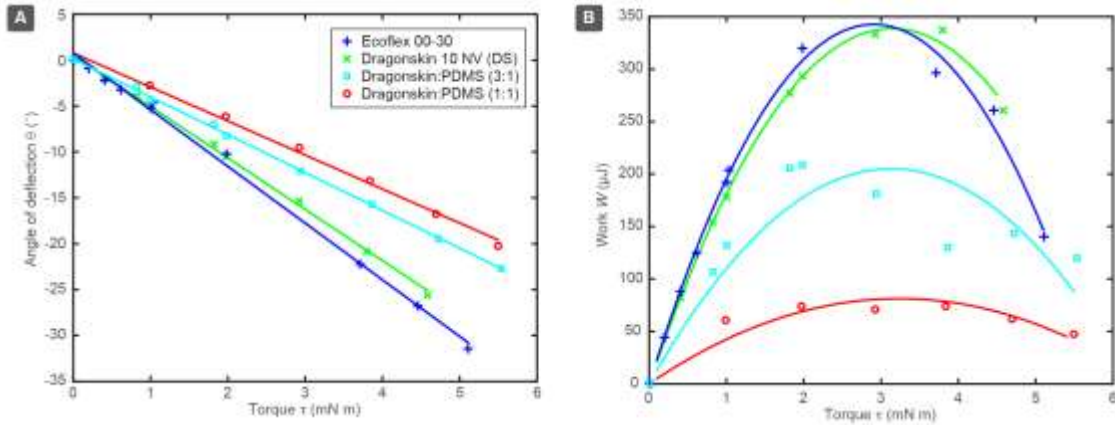


Figure S 3: This figure extends Figure 2 in the main text. (A) Deflection angle of the rod, when different loads (torques) are applied, without applying negative pressure. (B) Mechanical work done by actuators, when different loads are applied. As the maximum actuation amplitude decreases with increased load, there is an optimal loading torque (around 3 mN.m) for getting

maximum work done. Maximum work decreases for actuators fabricated with stiffer elastomers because they are not completely actuated at atmospheric pressures.

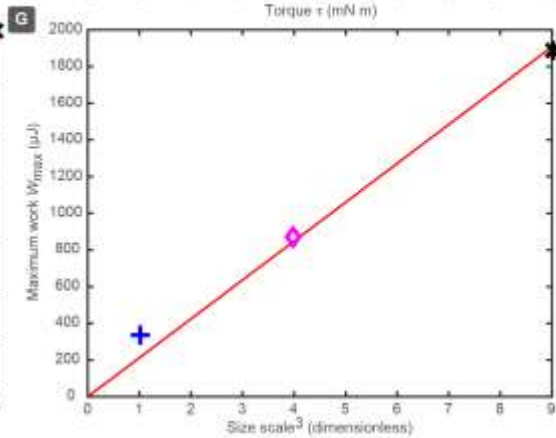
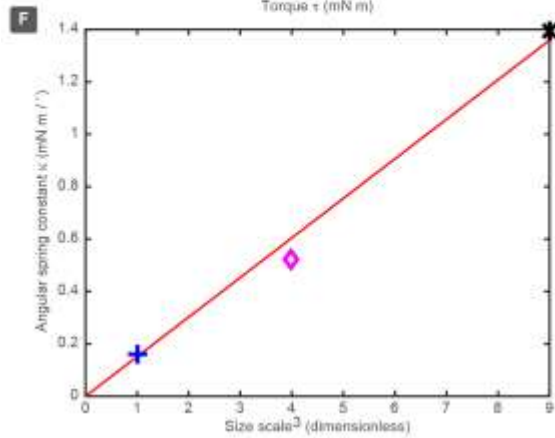
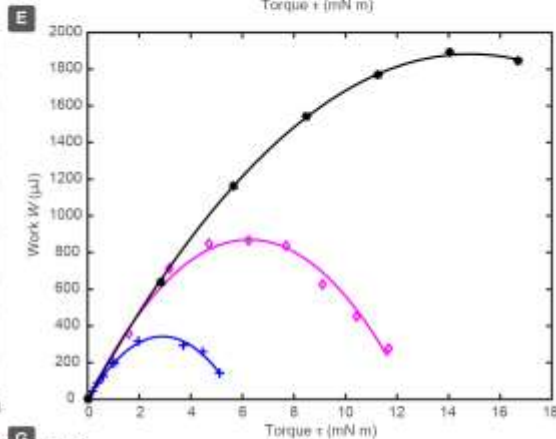
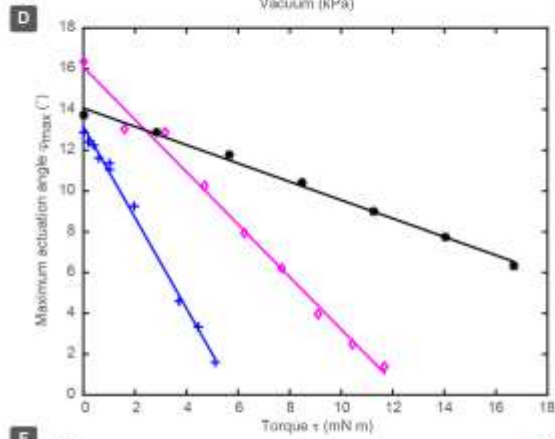
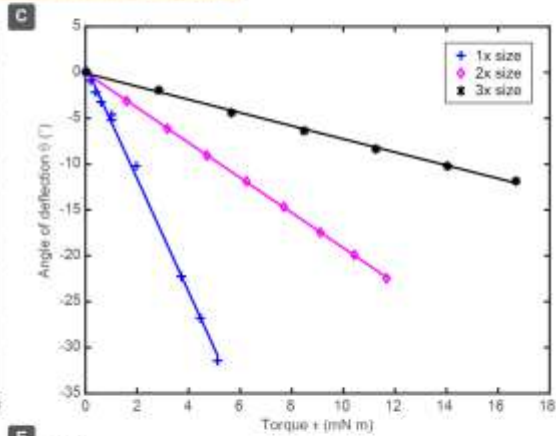
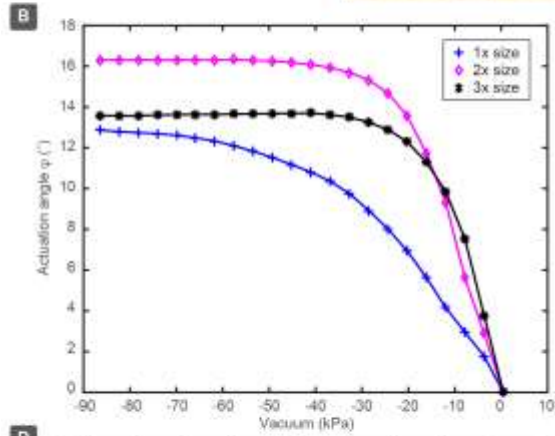
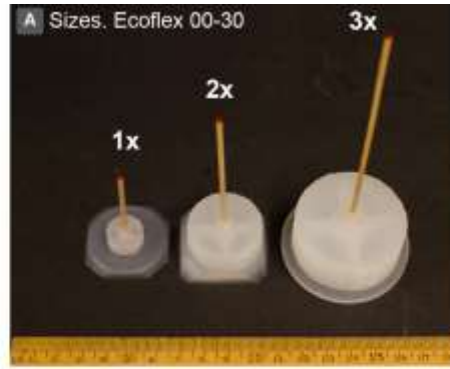


Figure S 4: The effect of scaling (1x, 2x, 3x) on the performance of actuators. In these cases, all dimensions of actuators were scaled linearly (1x is the design presented in Figure S1 and used for testing differences in materials and number of chambers). These actuators had four chambers and were fabricated in Ecoflex 00-30. (A) Photos of three different scales of actuators next to each other. (B) Actuation angle depending on applied pressure (no load). (C) Deflection angle depending on load (no negative pressure). (D) Maximum angle of actuation in the case of different loads. (E) Maximum mechanical work done by actuators in the case when different loads were applied. (F) Scaling of angular spring constant κ depending on size (should scale cubically with size). (G) Scaling of maximum mechanical work done by actuator (should scale cubically with size).

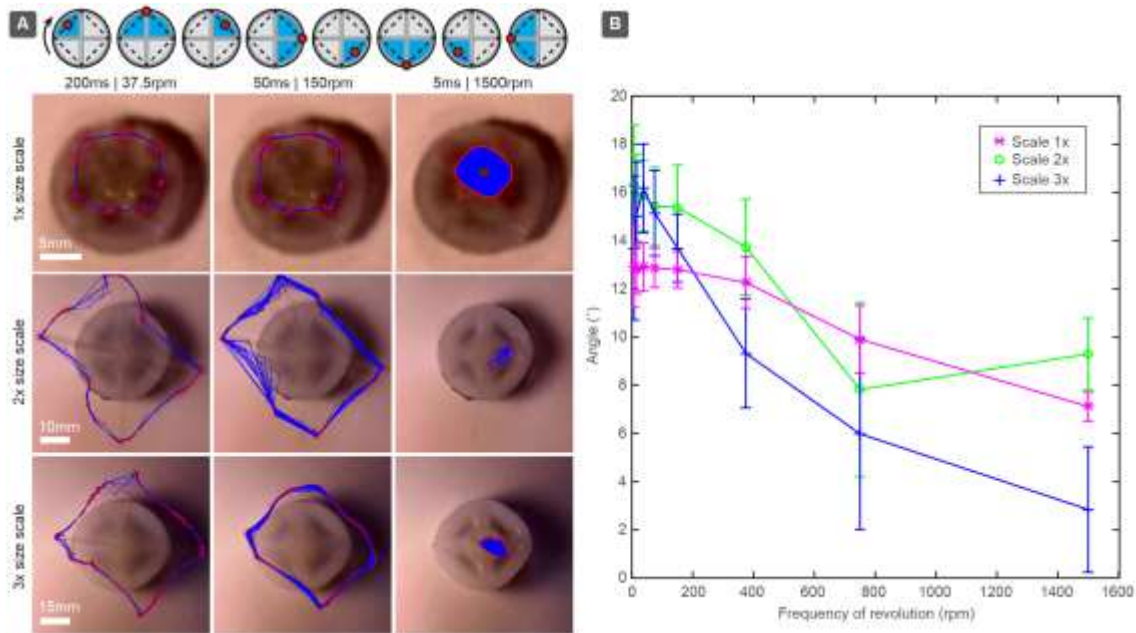


Figure S 5: The effect of scaling the actuator on the trajectory and angle of deflection during revolution. (A) Images showing 1x (the size used for varying materials and number of

chambers), 2x, and 3x actuators and their trajectories. (B) The maximum angle of deflection as a function of frequency of revolution as the actuator is scaled in size.

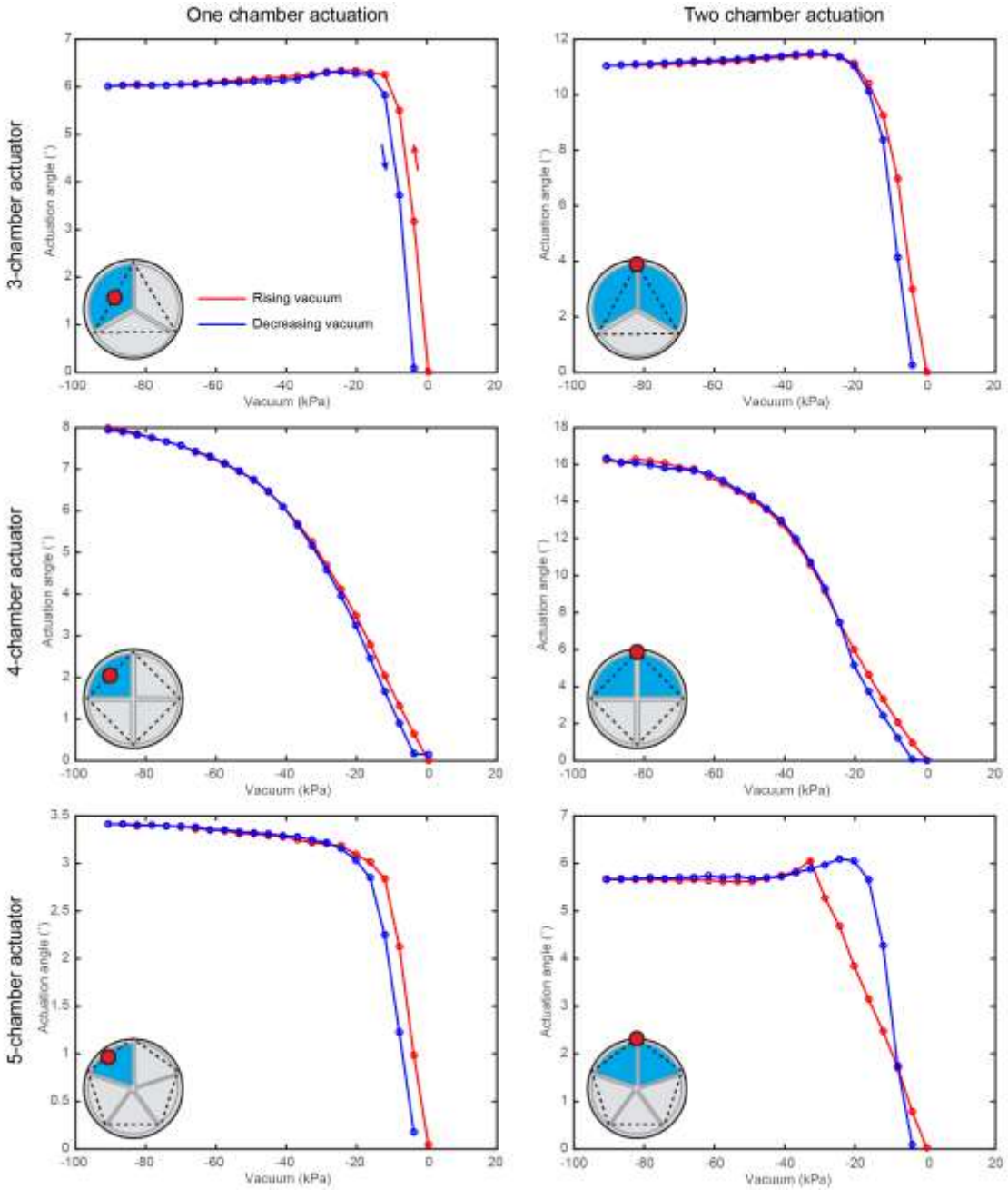


Figure S 6: Hysteresis in actuators as the negative pressure is varied. Pressures are scanned from 0 to vacuum (red) line and back to atmospheric pressure (blue line). We compare different number of chambers and also the differences between the actuation of one or two chambers.

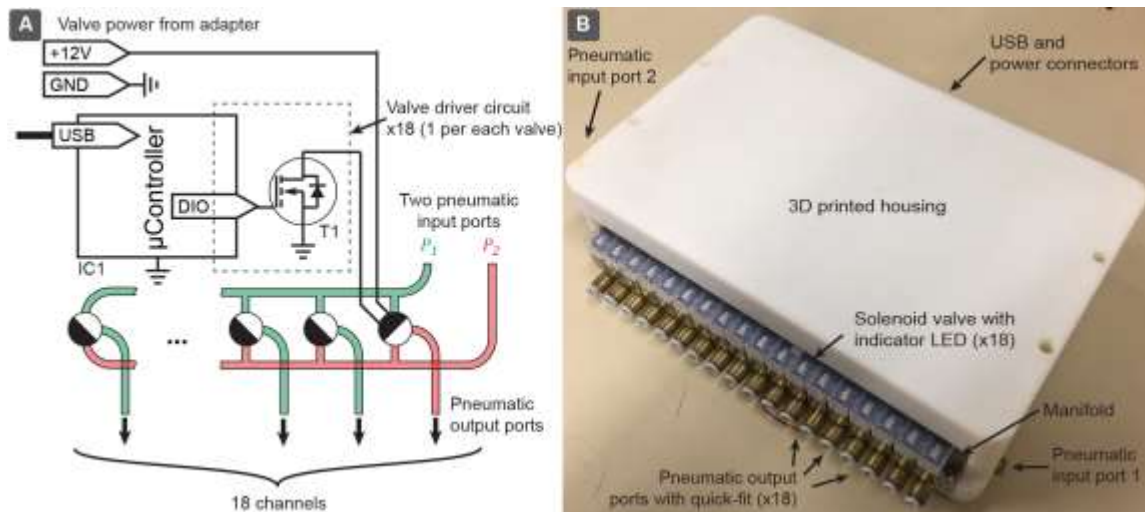


Figure S 7: Schematic layout and image of the valve controller.

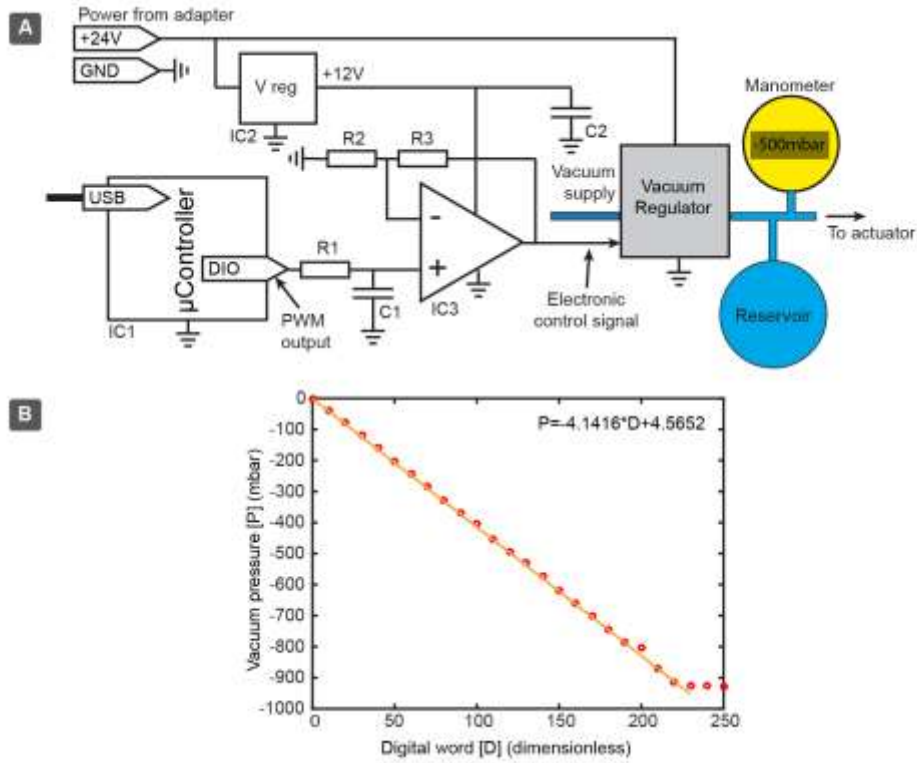


Figure S 8: (A) Schematic of the electronically controlled negative pressure regulator. (B) Calibration of the negative pressure to the digital word.

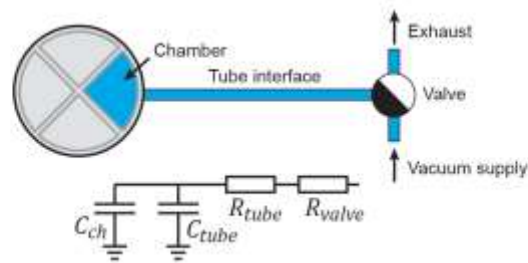


Figure S 9: RC-circuit analog of interfacing the actuator through valve and tubing. This schematic has been used to develop a crude model for estimating time constants (RC) for the pneumatic loading of the actuator.

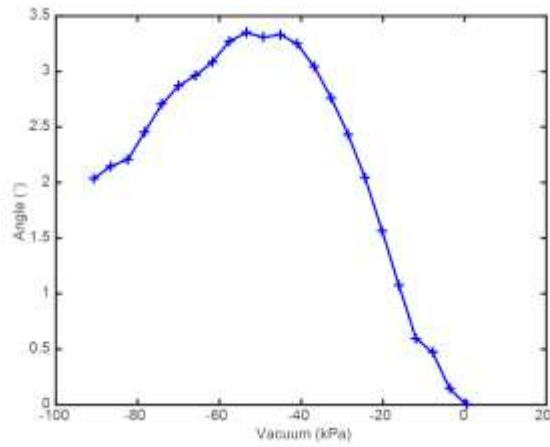


Figure S 10: The actuator can fail if the load is too high. Here, the actuator was fabricated in Ecoflex 00-30 and 4.5mN.m of torque was applied. The rod can detach from actuator because of the collapse of compartment along the rod's axis. Thus, the actuator was unable to lift the load as well and the angle of actuation decreased at high negative pressure.

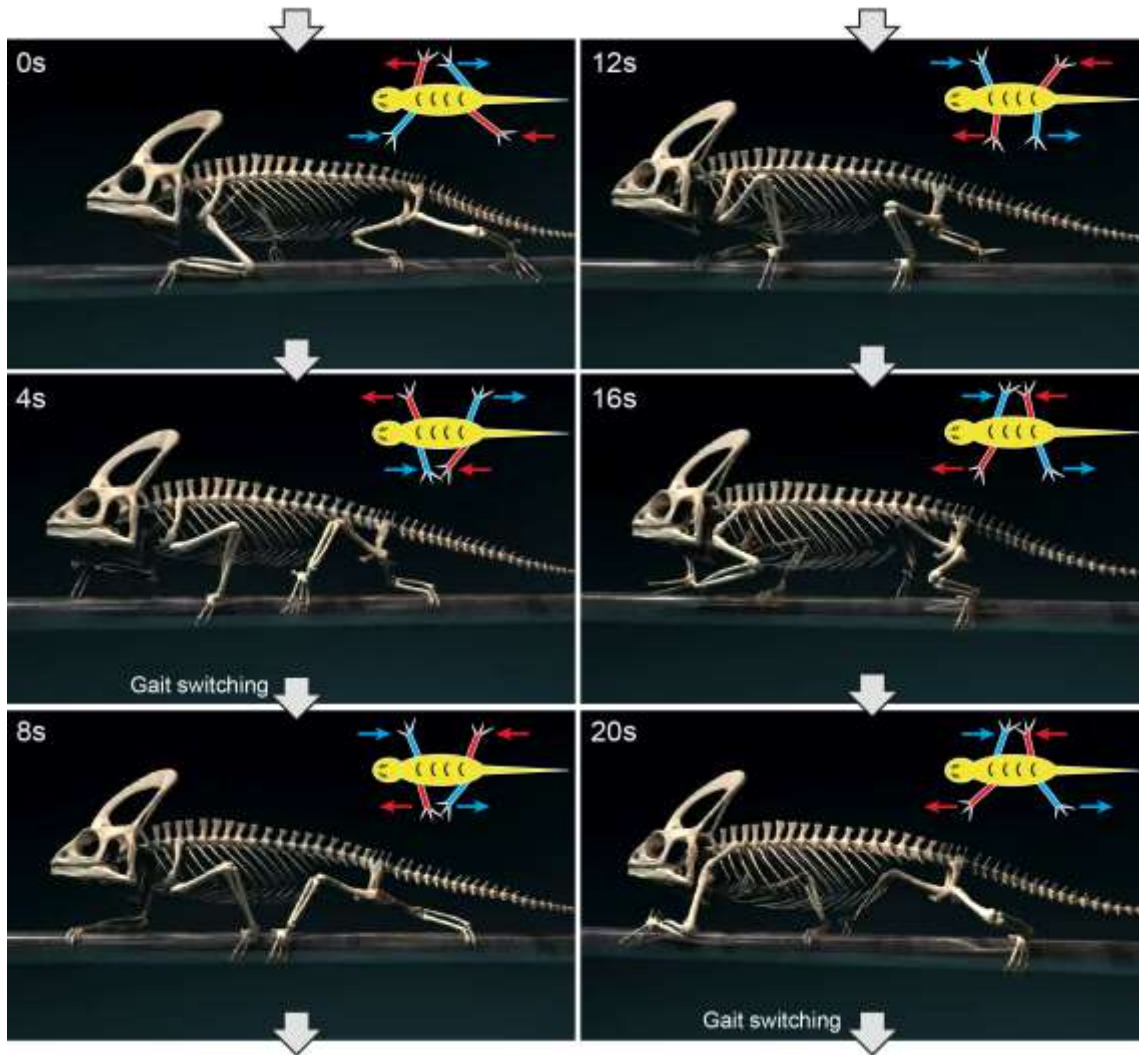


Figure S 11: Dorsal view of the animation of the gait of the reptile *Chamaeleo calyptratus*. The frames were extracted from Movie S7 of the work by Fisher et al.³ The time stamps represent the time elapsed in the video. Schematic illustration of the gait on the top right corner of each frame represents that the diagonal legs move (almost) simultaneously. Limbs moving forward are colored in red and limbs applying force backwards are colored in blue.

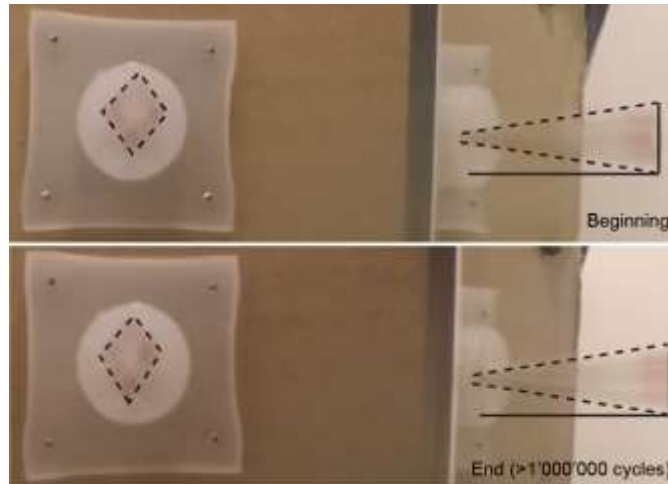


Figure S 12: The amplitude of oscillation remains unchanged for the cVAM actuator after operating it for over 10^6 cycles. The top image shows the trajectory (left part of the image shows the front view of the actuator) and amplitude (right part of the image shows the side view of the actuator) before the million cycles and the bottom image shows the actuation after the million cycles.

Supplementary videos

Movie S1 A single actuator moves the rod by 16° when vacuum is applied.

Movie S2 Demonstration of stirring with plastic beads.

Movie S3 Characterization of the cVAM for different frequencies of operation and different pressures.

Movie S4 Demonstration of stirring while delivering fluid using cVAM.

Movie S5 A four-legged “walker” that is operated by the action of four cVAMs.

Movie S6 A propped up view of the four-legged “walker.”

Movie S7 The movement of a single actuator in the “walker.”

References

1. Russo S, Ranzani T, Gafford J, Walsh CJ, Wood RJ. Soft Pop-up Mechanisms for Micro Surgical Tools: Design and Characterization of Compliant Millimeter-Scale Articulated Structures. *IEEE Int Conf Robot.* 2016: 750-757.
2. Yang D, Verma MS, So J-H, Mosadegh B, Keplinger C, Lee B, Khashai F, Lossner E, Suo Z, Whitesides GM. Buckling Pneumatic Linear Actuators Inspired by Muscle. *Adv Mater Technol.* 2016; 1(3): 1600055.
3. Fischer MS, Krause C, Lilje KE. Evolution of Chameleon Locomotion, or How to Become Arboreal as a Reptile. *Zoology.* 2010; 113(2): 67-74.