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Supplementary Materials for

Electronics with shape actuation for minimally invasive spinal cord stimulation

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The PDF file includes:

Figs. S1 to S8
Finite element analysis of MI-SCS device
Fabrication schematics
X-ray optimization
Surgical procedure
Pneumatic pressure testing
Legends for movies S1 to S3

Other Supplementary Material for this manuscript includes the following:

(available at advances.sciencemag.org/cgi/content/full/7/26/eabg7833/DC1)

Movies S1 to S3

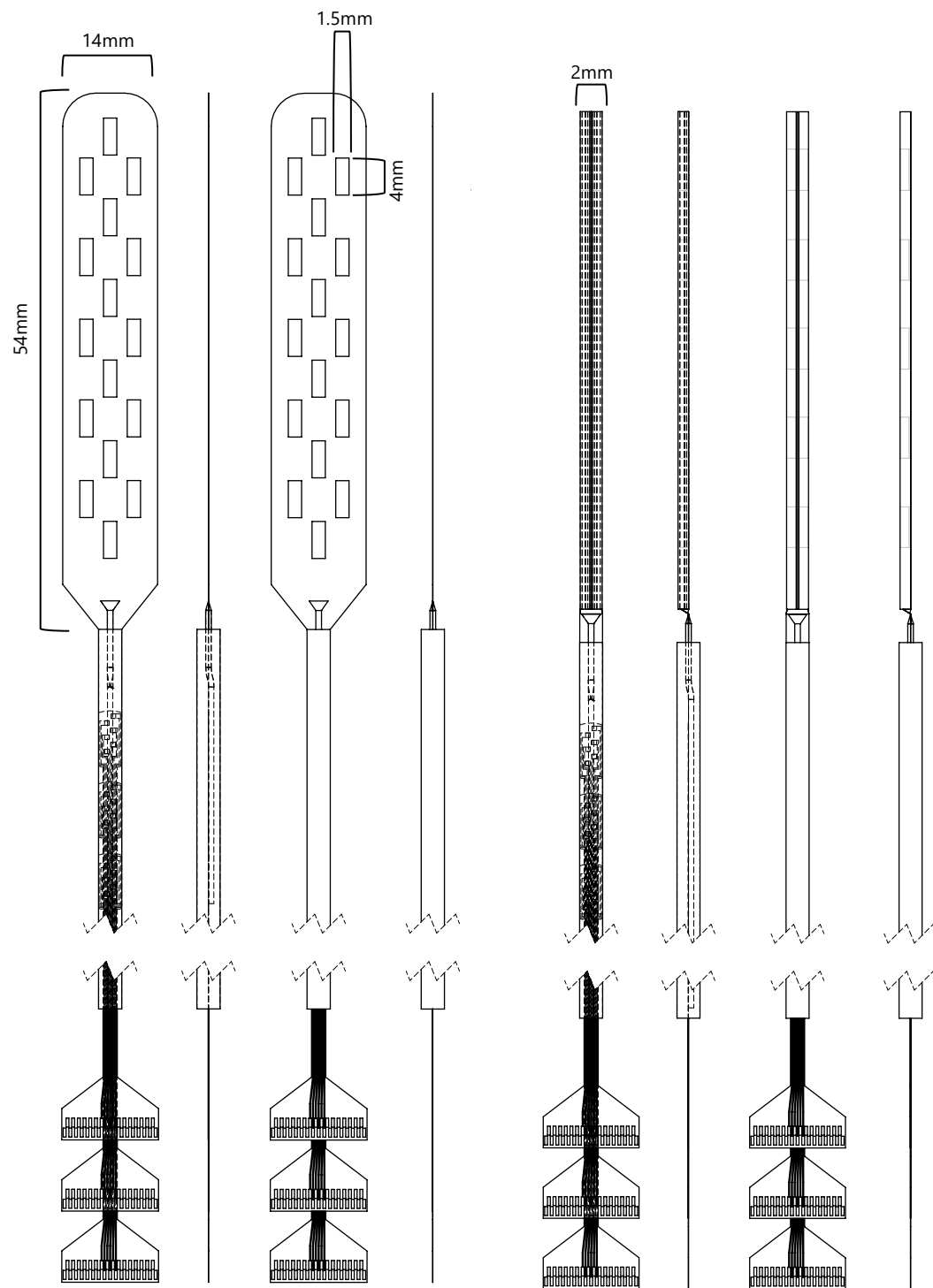


Figure S1

Drawings of the proposed MI-SCS device structure with relative dimensional information displayed. The four images on the left show the device in an unrolled configuration, the four images on right show the device in its rolled configuration.

Finite Element Analysis of MI-SCS Device

A nonlinear, hyper elastic, finite element mechanical simulation using composite shell elements with a reference element size of 500µm, solving the governing equation 1 of the main thin films composing the SCS was performed; although the current lack of specific material data is a constraint for a more specific quantitative analysis, a qualitative analysis matching the experimental behaviour of the device using a reference material properties(30) was achieved. Figures S2-3 show the specific possible stress concentrations and deformations. It is shown that the microfluidic channels, the layering of the materials and different material properties help to mitigate the excessive vertical expansion of the device.

$$K(\{u\})(u) = \{F\} \quad (1)$$

Where $K(\{u\})$ is the stiffness term as a function of the displacements term u , and F is the generalised forces term.

Two supplementary figures (S2, S3) are provided observing stress and total deformation under pneumatic pressure. These are subdivided into devices without island features intended to restrict the AP expansion of the device and with these features, comparing the apparent and predicted behaviour of both.

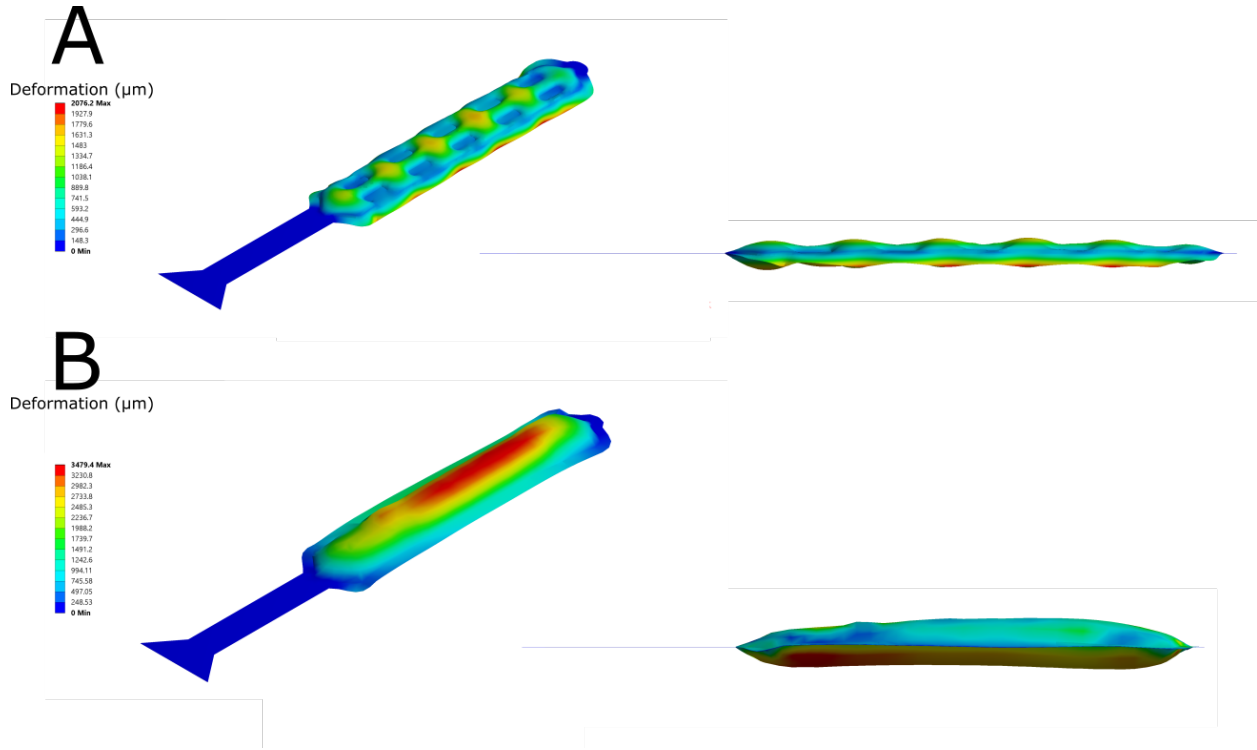


Figure S2

Total deformation model of two MI-SCS devices under pneumatic pressure (2kPa). One device represents the final MI-SCS with engineered silicone islands (S2.A), the other device has an open 'balloon' fluidic (S2.B). The models show the reduction in AP-expansion that can be achieved when top-bottom silicone islands are engineered into the device.

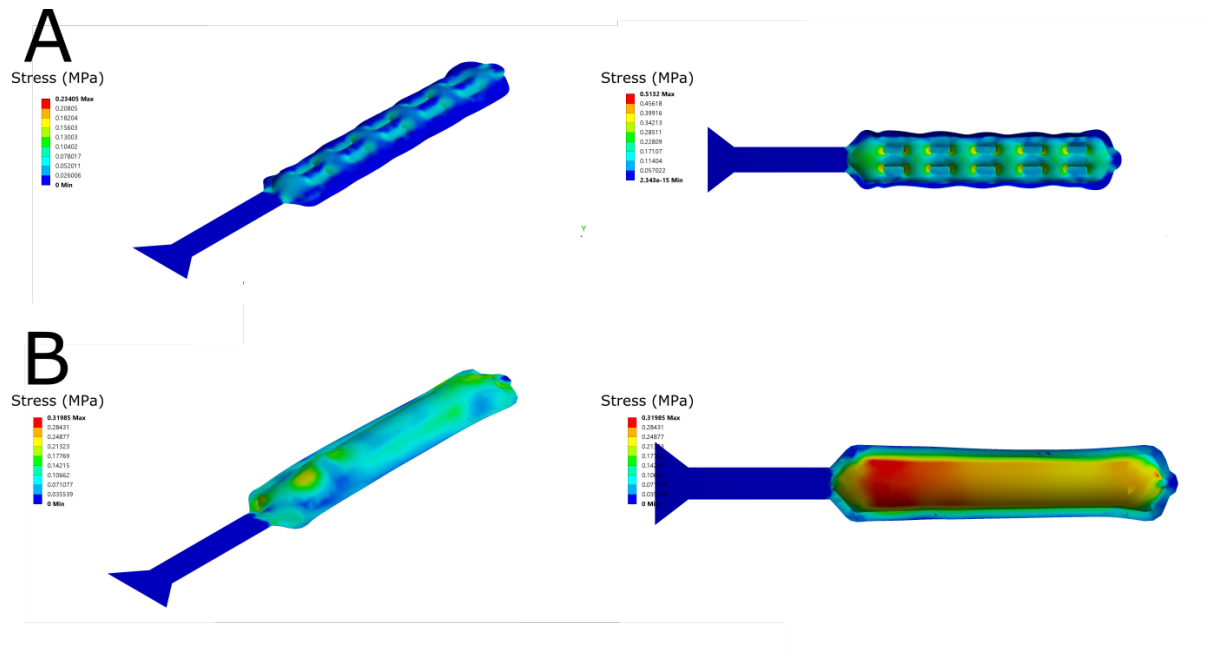


Figure S3

FEA modelling of the final MI-SCS device (S3.A), with engineered silicone islands and without islands (S3.B), showing relative stress points following an applied 2kPa of pneumatic pressure.

Fabrication Schematics

Figures S4 and S5 outline the specific microfabrication, soft fabrication and packaging steps that were carried out to create functional MI-SCS devices.

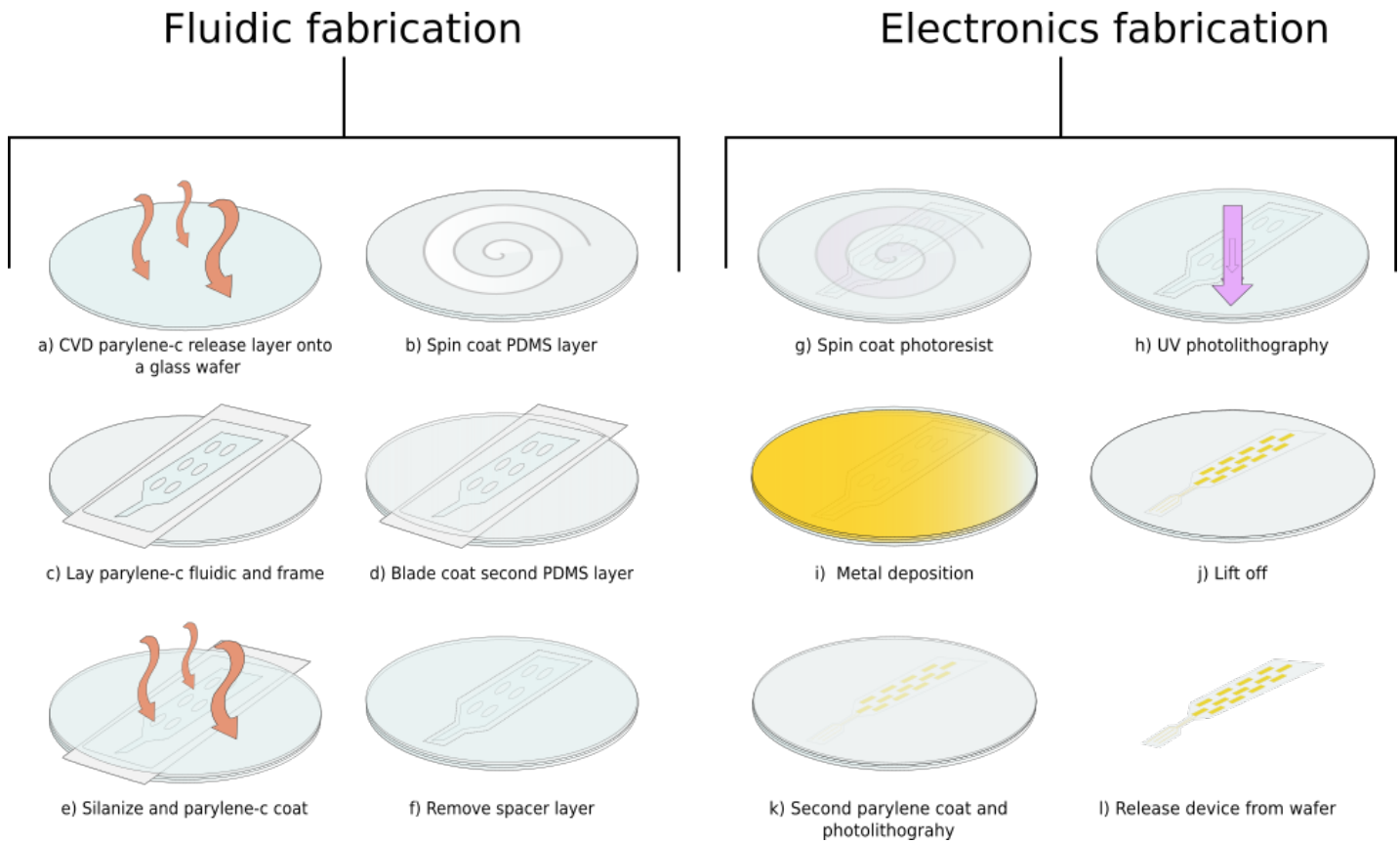


Figure S4

Process flow for the soft lithography and photolithography steps required for fabrication of the MI-SCS paddle.

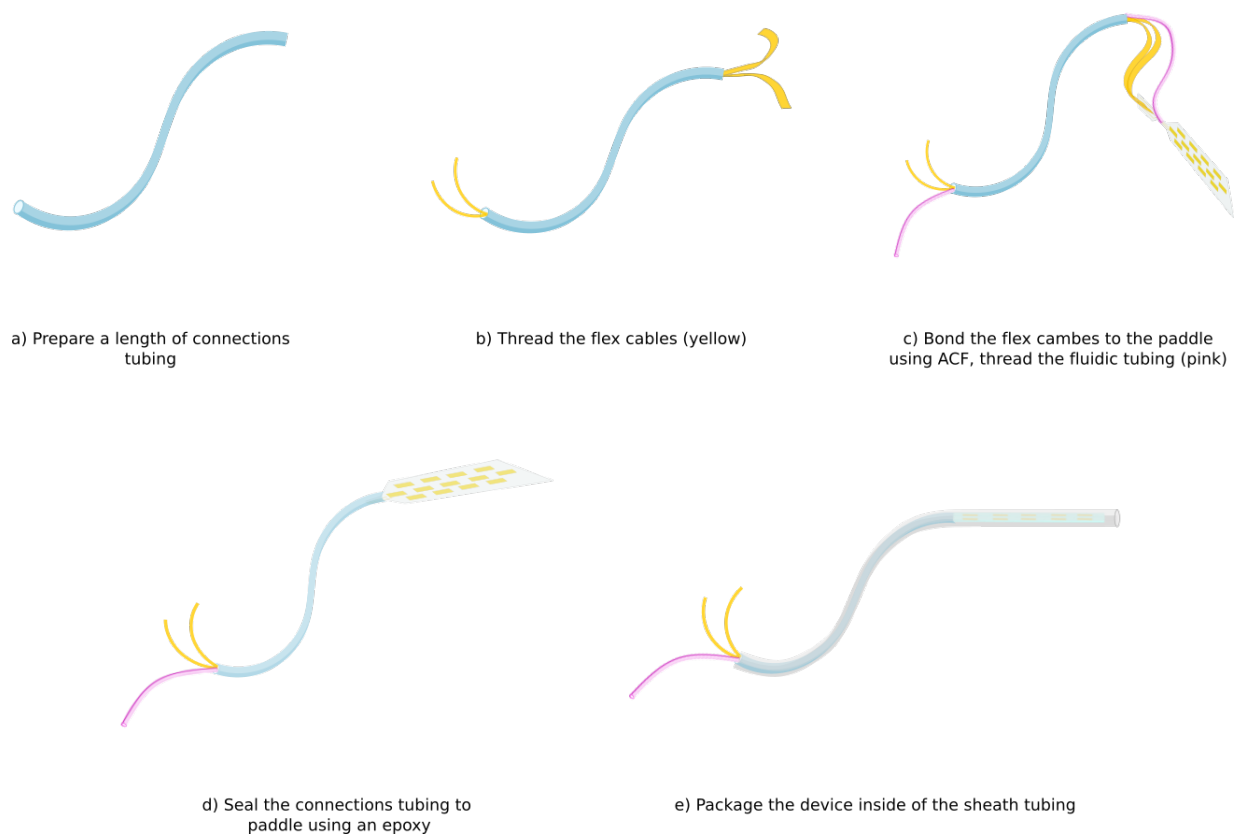


Figure S5

Process flow for the packaging of the MI-SCS device. Once the device paddle is released from the wafer it must be packaged to fit inside the delivery tube (introducer). Electrical cables and fluidic tubing are encased within a polymeric tube (connections tube) for protection.

X-ray Optimization



Figure S6

Additional X-ray marker images. (A) x-ray images of a commercially available barium infused silicone (Nusil MED2-4900, Polymer Systems UK) at 50 μ m thickness (left) 100 μ m (center), and 200 μ m (right). (B) Image of a custom cast barium sulphate infused silicone (40%w/w), 0.5mm in thickness and 0.5mm (left), 0.7mm (center) and 1.4mm (right) in width. (C) Barium Sulphate infused silicone prepared in-house at 50%w/w loading capacity 1000 μ m thickness (left) and 80%w/w loading capacity at 1000 μ m (right).

Surgical Procedure

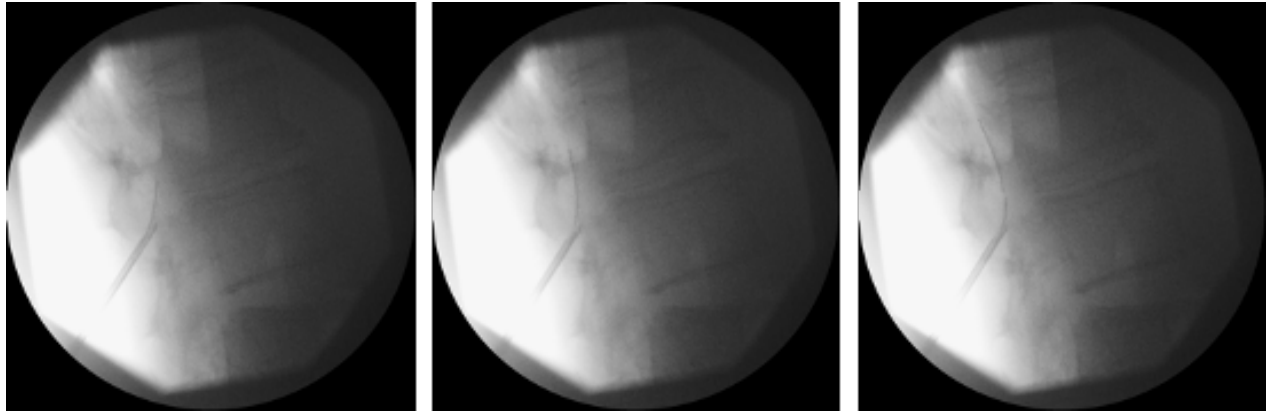


Figure S7

Fluoroscopy images taken laterally of the MI-SCS being inserted. The image sequence from left to right shows the device exiting the Tuohy needle and travelling epidurally along the spinal cord rostrally. These images show clearly the device exiting the needle and being translated up the spinal cord, epidurally on the dorsal side.

Pneumatic Pressure Testing

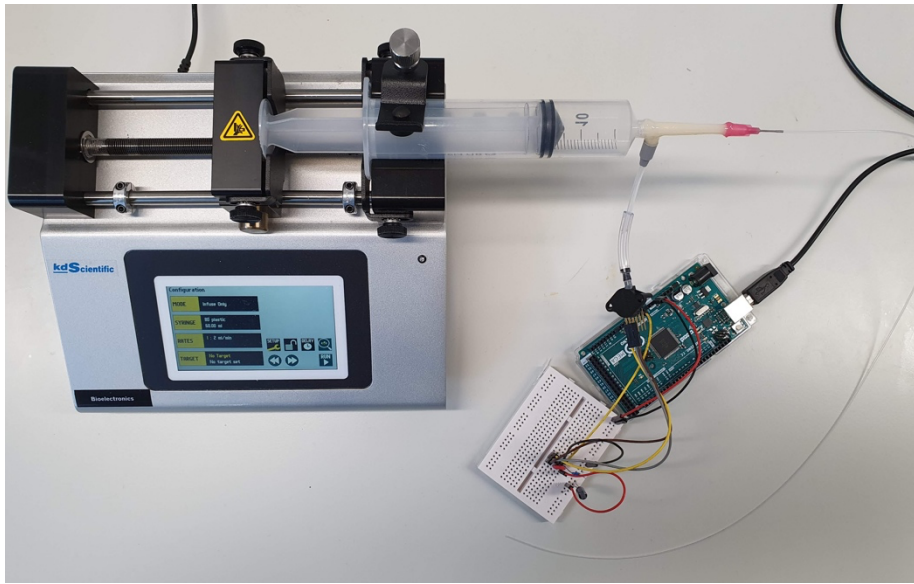


Figure S8

A rig designed in-house to pressure test the devices during actuation. A syringe pump drives the air flow in a forward direction at 1mL/min. A T-piece is used to connect the device to a pressure sensor, this is interpreted by an Arduino Mega which provides a pressure readout to a connected PC. Photo credit: Ben Woodington, University of Cambridge.

Movie S1. MI-SCS device expanding within an in vitro model

This movie shows a device expanding under air pressure within an *in vitro* model.

Movie S2. FEA showing deformation for the final MISCS device expanding under pressure (2kPa)

This movie shows the FEA for deformation, a summary is provided in Figure S2.

Movie S3. FEA showing relative stress for the final MISCS device expanding under pressure (2kPa)

This movie shows the FEA for device stress, a summary is provided in Figure S3.