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Functionalised Capacitive Microfluidic Force Sensors for Orthopaedic Implants

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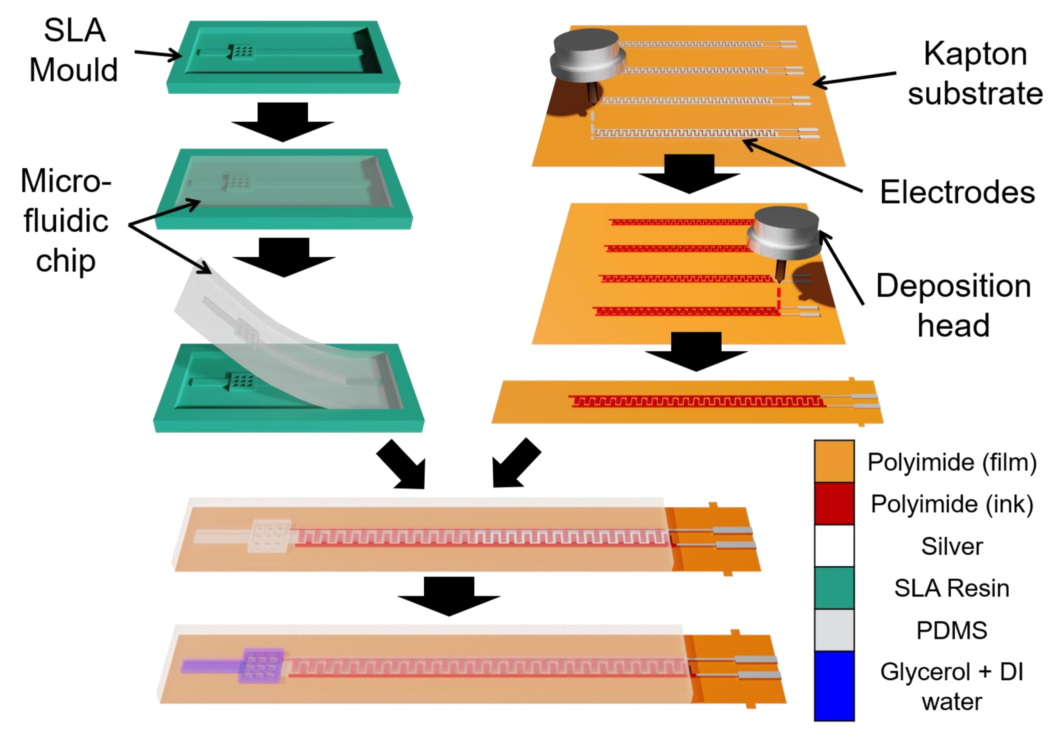
INTRODUCTION

- The average age of a patient requiring a hip replacement is decreasing[1], so implants must survive greater activity levels and higher stresses than those exerted by older, less active patients.
- Quantitative force feedback during surgery could provide more accurate implant positioning, increasing the average lifetime and reducing the need for revision surgery[2,3,4].
- However, there are currently no commercially-available force sensors capable of providing this information within the small and complex hip joint.

SENSOR FABRICATION



Microfluidic chip: made from elastomer (such as PDMS or Formlabs' Flexible Resin) and produced using a stereolithography (SLA) 3D-printed mould, or by directly 3D-printing the chip.

Interdigitated electrodes: produced by aerosol-jet printing onto a Kapton (polyimide, PI) film using silver nanoparticle ink, as per the group's previous work[4,5]. An insulating PI layer was printed on top of the electrodes.

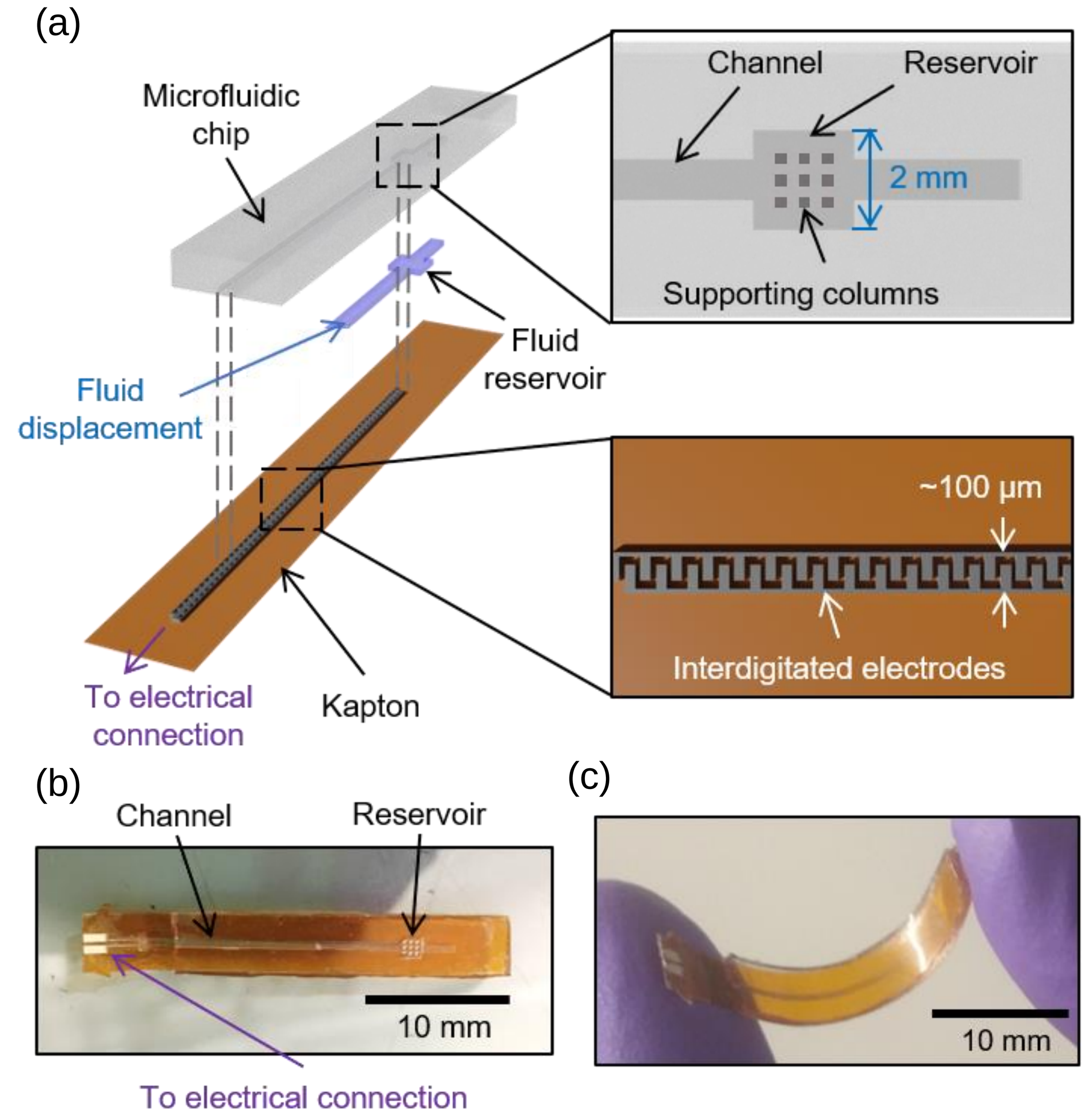
Assembly: the microfluidic chip and electrode layer were bonded using a primer and silicone glue. Once the glue dried, the reservoir was filled with a 2:1 by volume glycerol-water mixture.

Mock implant geometry: two cups were fabricated using SLA 3D printing. The sensors were placed into grooves within the outer cup.

DESIGN AND OPERATION

- An elastomeric layer with the reservoir and microchannel was bonded to a Kapton layer with aerosol-jet printed interdigitated electrodes (Fig. 1a).
- Applied force to reservoir displaced fluid along the channel.
- Fluid overlap increases the capacitance of the electrodes.
- Sensors operational at same curvature as hip joint.

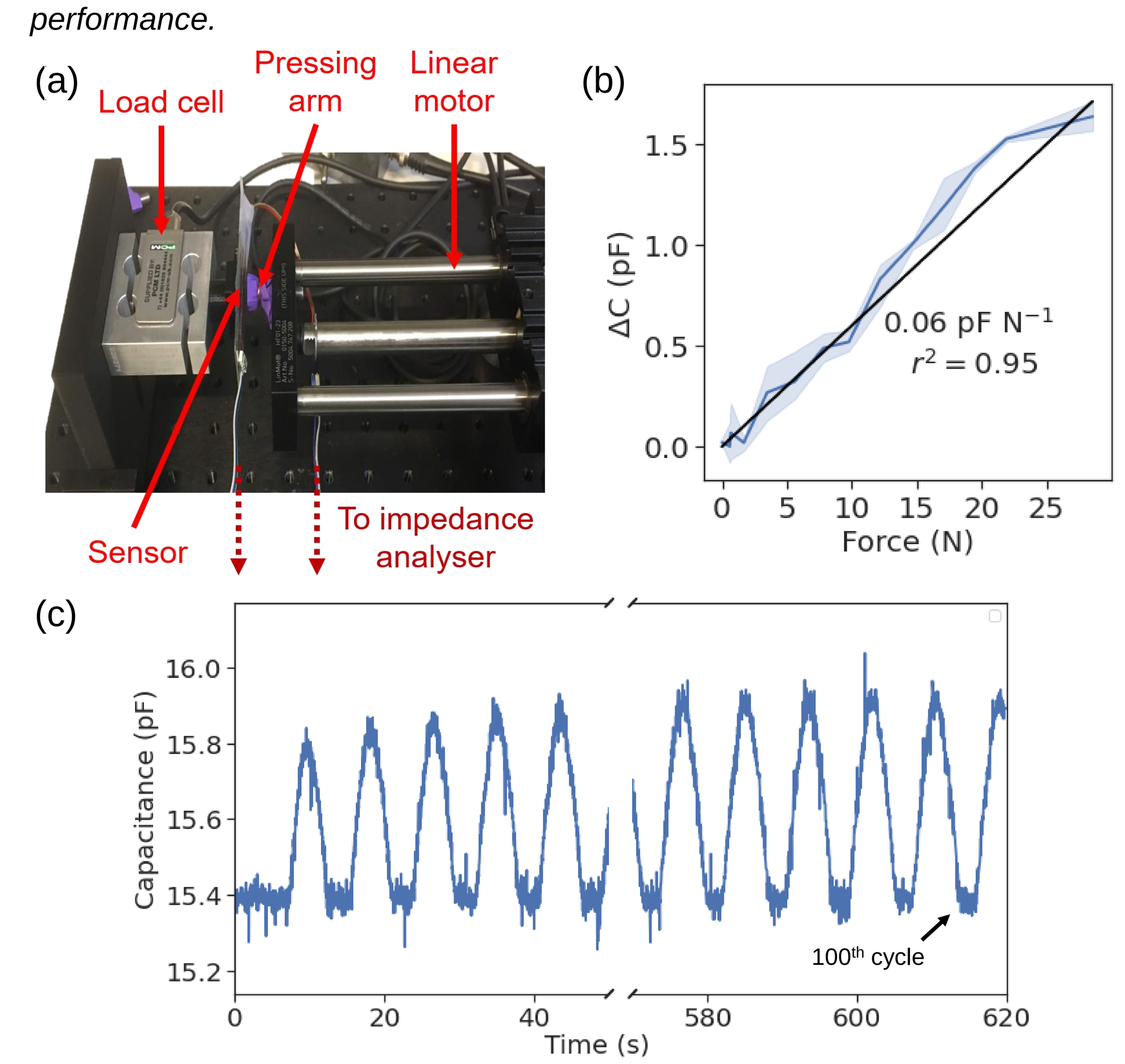
Figure 1: sensor design and operation. *(a) Schematic of microfluidic force sensor, showing the design of each layer. (b,c) Photographs of the sensor, showing its flexibility.*



CALIBRATION

- Calibration up to 25 N achieved using a linear motor (LinMot, Fig. 2a).
- Linear capacitance-force relationship was observed (Fig. 2b).
- Linear regression obtained sensitivity of 0.06 F N^{-1}, $r^2 = 0.95$.
- Fatigue life of sensors exceeded 100 cycles (0-10 N applied force) without significant change in device performance (Fig. 2c).

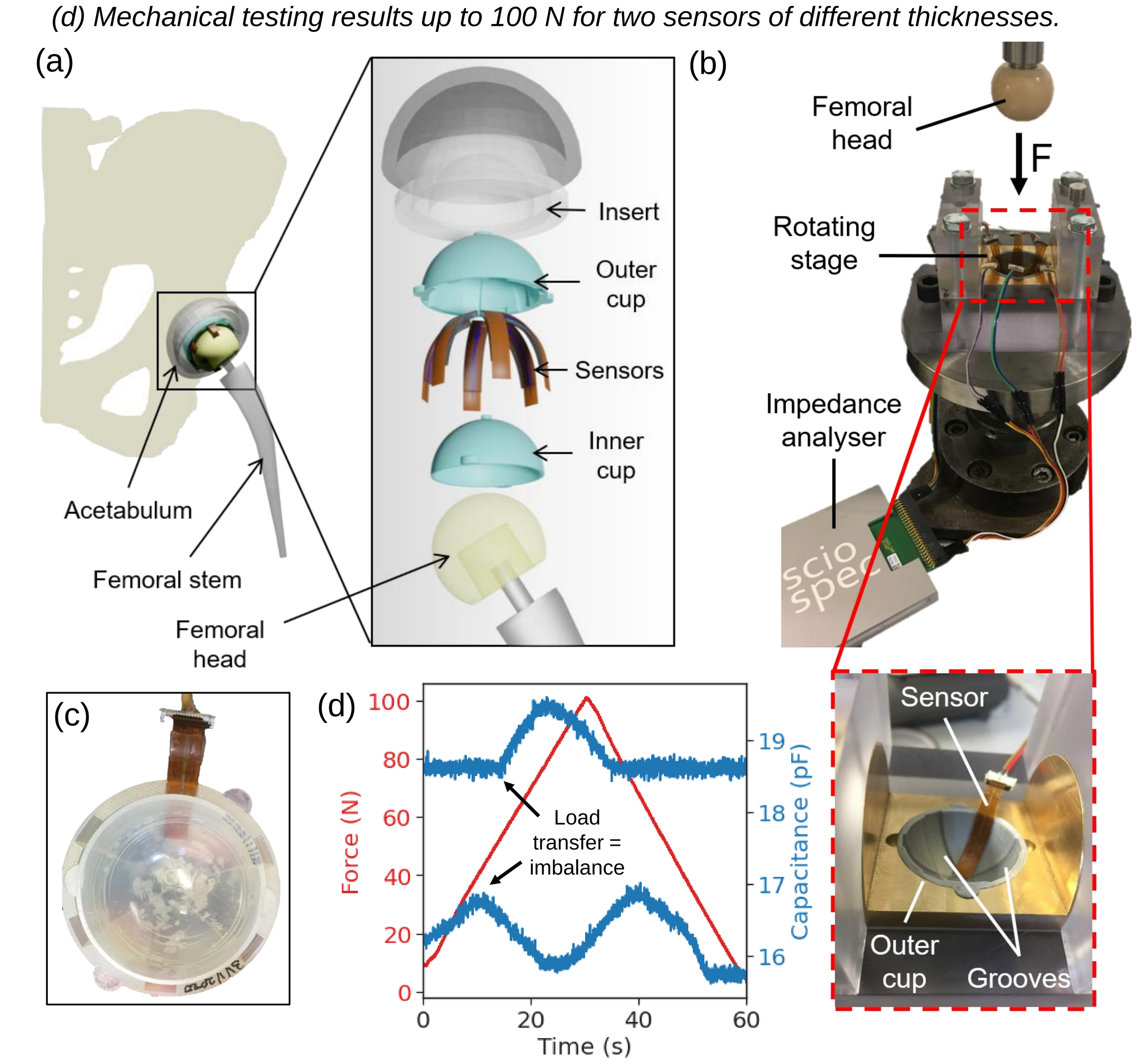
Figure 2: sensor calibration. *(a) Linear motor setup. (b) Calibration of sensor up to 20 N to determine sensitivity (shaded area = 95% confidence interval). (c) Fatigue life: at least 100 cycles without significant change in device performance.*



PROOF OF CONCEPT

- Sensors of different thicknesses incorporated into a 3D-printed mock hip implant (Fig. 3a).
- Mock hip implant housed in bespoke mechanical testing rig (Fig. 3b).
- Servohydraulic testing machine applied forces up to 100 N.
- Load transfer can be seen between two sensors of different thicknesses, indicating imbalance in the joint geometry.

Figure 3: incorporation of sensors into mock implant geometry. *(a) Exploded diagram of sensors incorporated into 3D-printed mock acetabular cups. (b) Bespoke mechanical testing rig, with mock acetabular cups with grooves to house the sensors. (c) Photograph of the two mock acetabular cups, with one sensor inside the groove. (d) Mechanical testing results up to 100 N for two sensors of different thicknesses.*



CONCLUSIONS

- A flexible, conformable, microfluidic force sensor was developed using low-cost, scalable additive manufacturing techniques.
- Sensors were incorporated into a mock hip implant geometry and loaded up to 100 N. Load transfer can be seen between sensors, indicating that they could be used to determine balance within a joint.
- Maximum force reached = 100 N, without failure.
- Sensitivity = 0.06 pF N^{-1} with $r^2 = 0.95$.
- Fatigue life = 100 cycles, without failure.

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