A Portable Soft Robotic Device Enabling Speculum-Free Cervical Assessment and Sampling

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Background

Cervical cancer is largely preventable through effective screening and early treatment, yet screening coverage remains suboptimal worldwide. In high-income settings, discomfort, embarrassment, and previous negative experiences with speculum examination contribute to reduced attendance [1]. In low- and middle-income countries, screening programmes are further constrained by shortages of trained providers, equipment, and clinical infrastructure [1].

Speculum-free and home-use technologies are emerging as a potential alternative, aiming to improve acceptability and broaden access to cervical visualisation and sampling without reliance on conventional instrumentation.

World Health Organization

NHS

Pledge: **eliminate** cervical cancer by 2040[3][4]

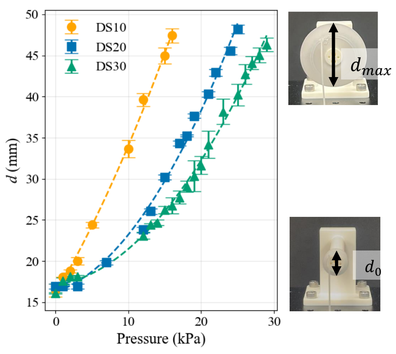
Design Parameters

Clinical Constraint	Design Response
Vagina is a collapsed lumen	Radial dilation ≥ 40 mm using a toroidal anchoring chamber (≈ 2× average cervix diameter) to locally stabilise the end effector, camera and instruments.
Variable cervix position	2 DoF distal control (axial rotation + planar bending) providing workspace coverage among common uterine positions.
Comfort limits	Low-pressure actuation (≤ 100 kPa), syringe-based input, sub-Newton to Newton-scale tissue forces
Cell sampling and visual inspection needed for triage	High-fidelity torque transmission through flexible shaft; rotation preserved under bending with minimal angular loss, acceptable transformation zone visualisation from robot PoV.

Table 1. *Summarises the clinical constrains and corresponding robot design considerations.*

Robot Characterisation

Dilation & Force Testing
Radial expansion and force measured as a function of inflation pressure, both unconstrained and within a compliant lumen.



Proof of concept testing indicates that:
- Anchoring chamber can expand to at least 2x average cervix diameter at low input pressure (< 30 kPa), regardless of material choice.
- Expansion of the anchoring chamber exerts < 2 N point force at < 40 kPa input pressure and the desired expansion diameter.
- Force is absorbed circumferentially by the lumen.

Fig 4. *Unconstrained diameter-pressure response for the anchoring chamber.*

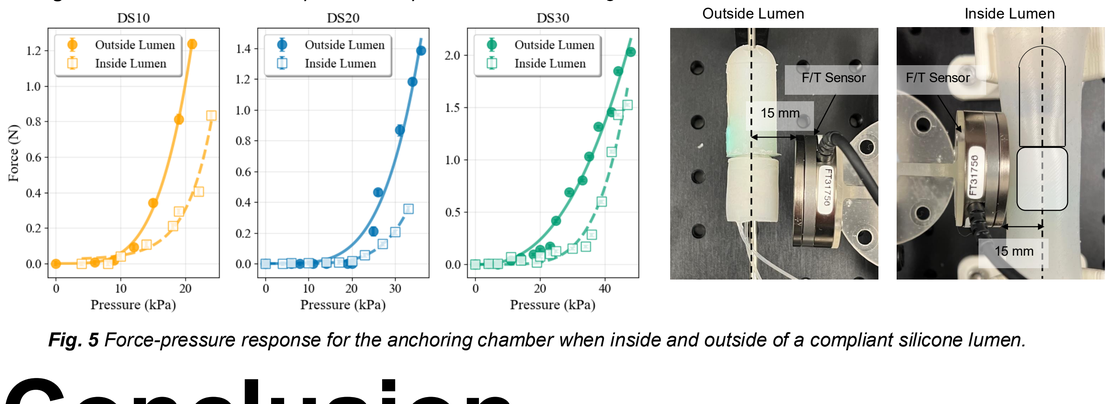


Fig. 5 *Force-pressure response for the anchoring chamber when inside and outside of a compliant silicone lumen.*

Conclusion

This work establishes a proof-of-concept soft robot design for robot-assisted cervical access, enabling visual inspection and cell sampling without a speculum, and opening pathways for use by non-expert operators and in low-resource settings.

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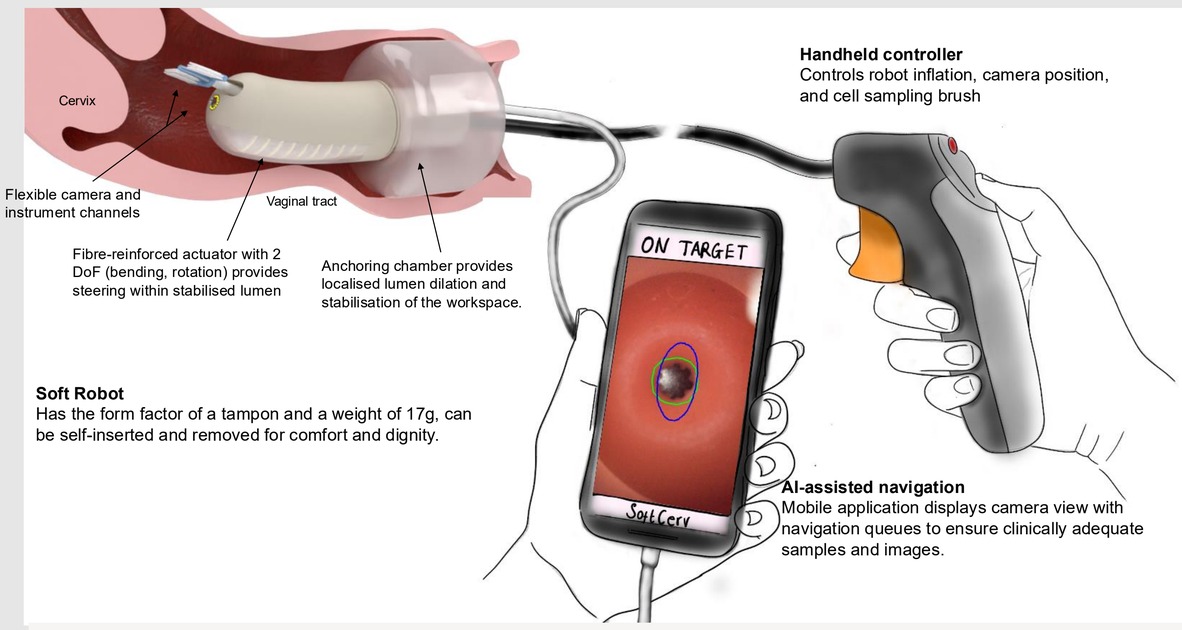


Fig. 3 *(Top) Artistic rendering of the handheld soft robotic device for cervical screening and visual assessment; the chip-on-tip camera provides guidance and real-time image segmentation aids non-experts to target anatomical ROIs for human-in-the-loop control.(Bottom) Proposed internal deployment of the soft robot in three user-friendly stages.*

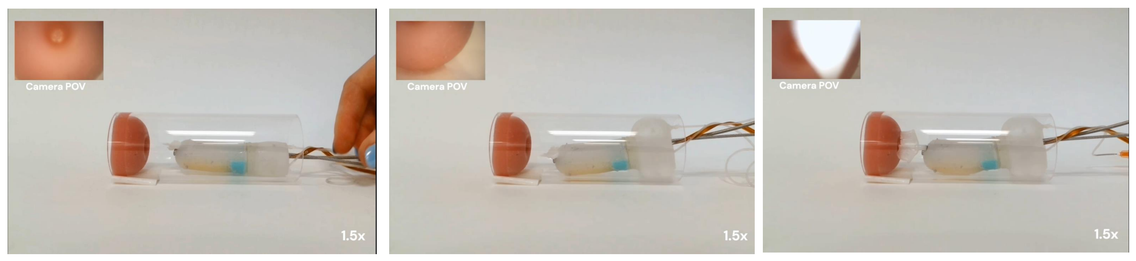
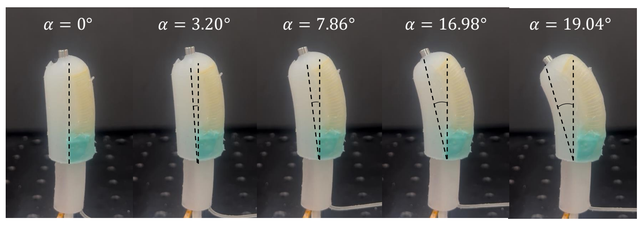


Fig. 4 *Frames from a video showiong the behaviour of the soft robot in a lumen environment. First, the robot simultaneously dilates the lumen while anchoring itself to create its own local workspace. The second actuator provides in-plane bending and axial rotation which provides dexterity to the camera and onboard instruments. Segmentation of the cervical os, based on fine-tuned EndoViT/DPT [5\, provides real-time guidance to the os and transformation zone, the region where samples must be taken from for screening.*

Steering & Workspace Mapping
Bending angle and lateral reach quantified under manual pneumatic actuation, with workspace mapped via EM tracking



Proof of concept testing indicates that:
- Bending angle at low actuation pressure (< 100 kPa) is sufficient reach average ectocervical region.
- Actuation achieved manually via 5mL syringe is adequate for required bending.

Fig. 6 *Actuator-camera-instrument assembly bending angle for increasing input pressure*

Phantom Testing
Time to full transformation-zone visualisation quantified across multiple cervix orientations in a custom cervico-vaginal phantom, measured over 10 trials.

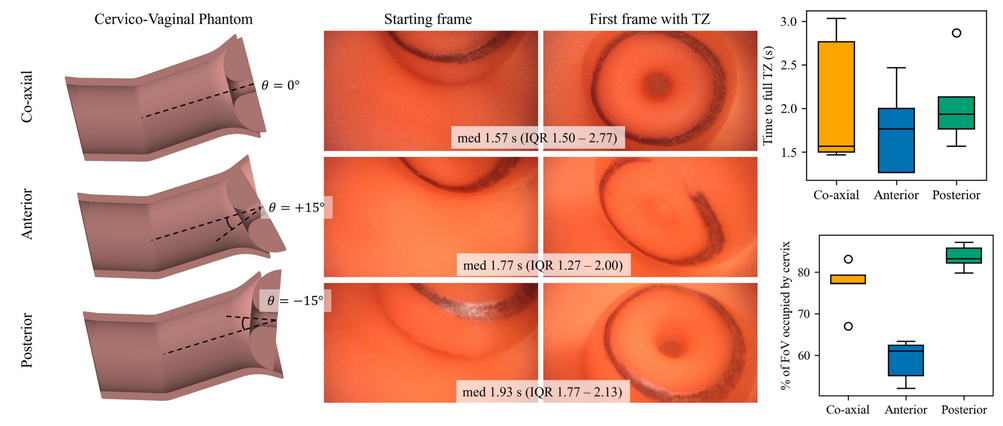


Fig. 7 *(Left) Phantom tests for three different cervix orientations. (Right) Time taken for robot to visualise the full transformation zone and % of cervix in camera FoV across 10 trials.*

References

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