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Differential Stretchable Strain Sensor System for Monitoring Penile Axial Rigidity in Erectile Dysfunction Assessment

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Introduction

Axial penile rigidity is essential for effective sexual intercourse, as it reflects the ability of the penis to withstand axial loading during penetration. Although this parameter is clinically important, most current diagnostic approaches focus primarily on radial rigidity and often rely on rigid components that may affect comfort and interfere with natural tissue mechanics. The work presented here represents an early step toward a soft wearable sensing approach, with the longer term aim of integration into patch or smart watch like healthcare platforms for assessing axial rigidity using mechanically compliant sensors that follow physiological deformation.

Aim

The aim of this work is to develop and demonstrate a soft, stretchable differential strain sensor system that enables passive assessment of axial penile rigidity without the application of externally applied testing loads.

Method

- Stretchable strain sensors were fabricated using printed electronics on a soft, biocompatible elastomer substrate suitable for large deformation and skin contact.
- Conductive paths were patterned using a stretchable silver-based ink to maintain stable electrical performance under strain.
- Two geometrically similar sensor designs with different mechanical stiffness were engineered to enable differential strain transfer.
- The sensors were designed for longitudinal placement, with deformation arising solely from axial elongation and without external forces.
- For future skin attachment, a medical-grade adhesive was selected to ensure secure fixation and skin compatibility.
- Bench-top characterization involved controlled axial elongation (up to 150%) with resistance monitoring using standard electrical readout to assess differential response and consistency.

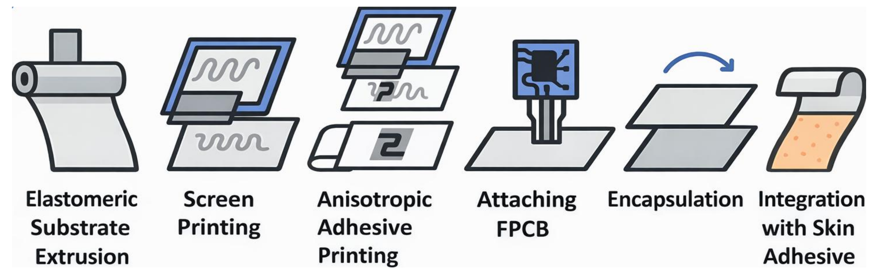


Figure 1: Overview of the fabrication and integration workflow used to realize the soft stretchable sensor system for axial rigidity assessment.

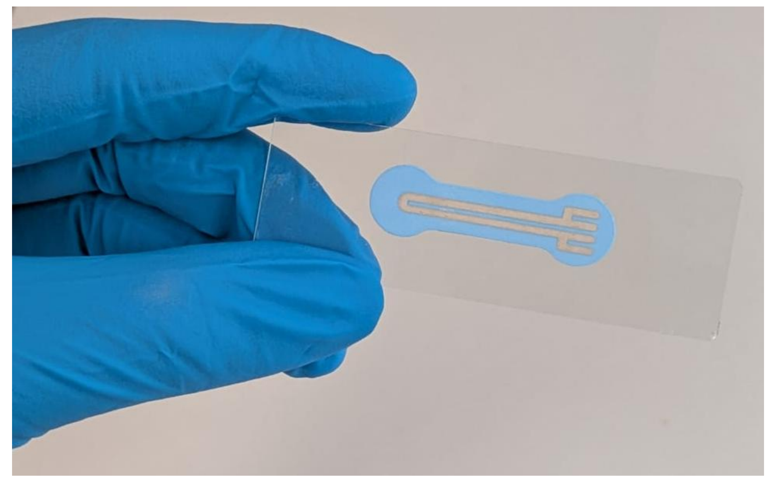


Figure 2: Unencapsulated printed stretchable strain sensor

Working Principle

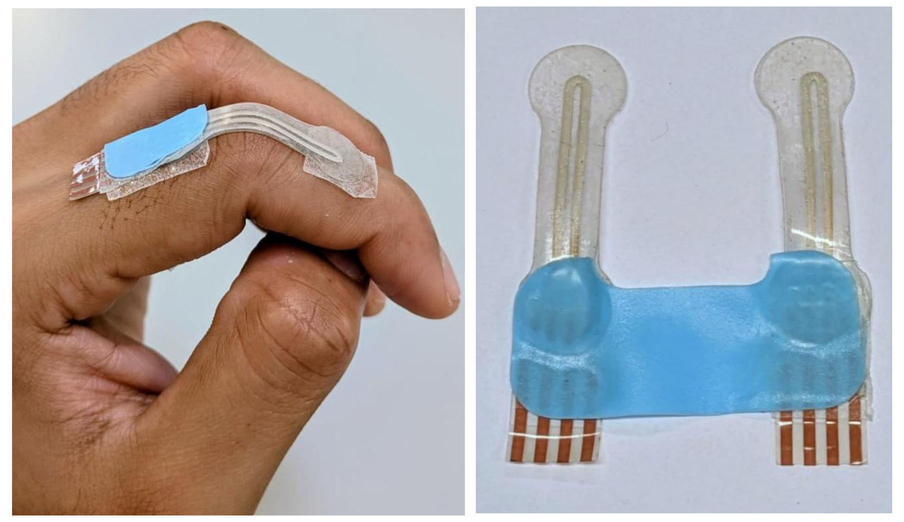


Figure 3: Dual stretchable strain sensor shown on skin and in its fabricated form, demonstrating flexibility, skin conformity, and suitability for wearable axial deformation sensing.

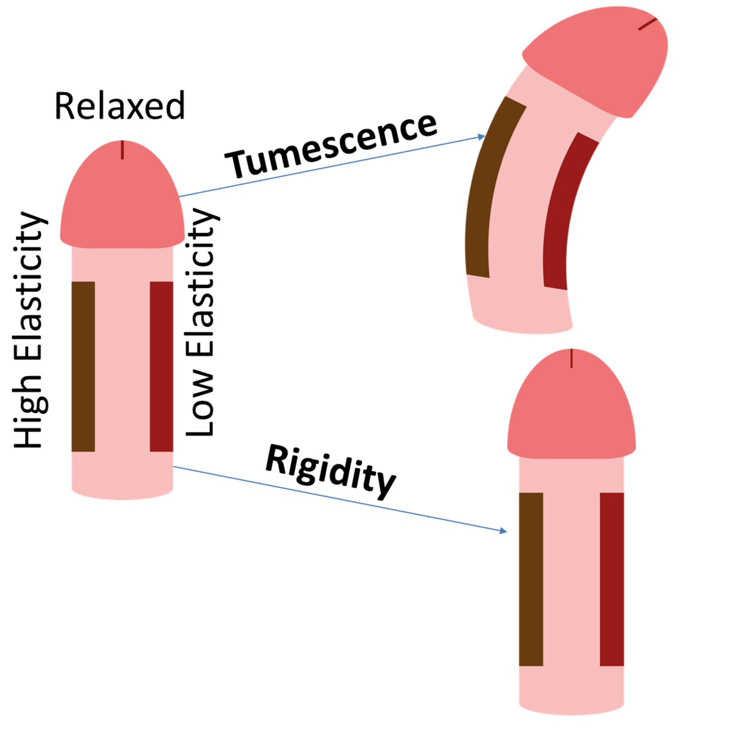
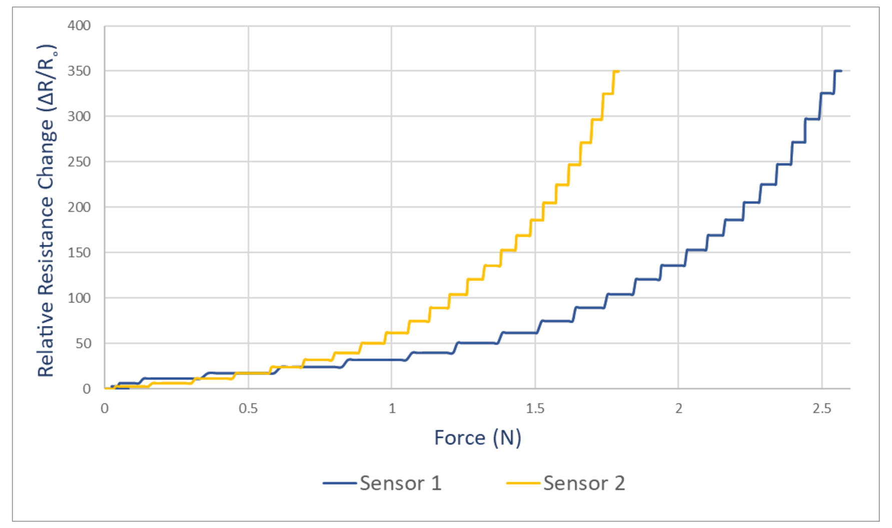


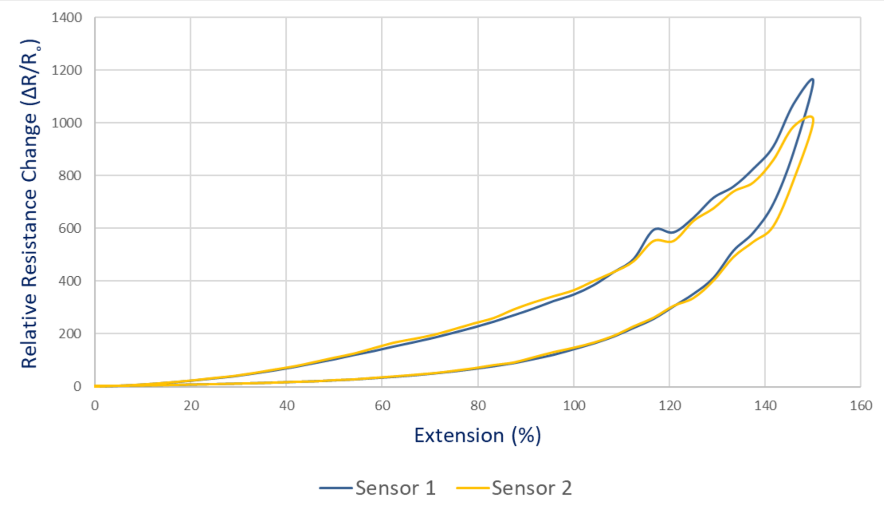
Figure 4: Schematic showing how axial penile rigidity is assessed using two stretchable strain sensors with different stiffness. When axial support is low, most deformation occurs in the softer sensor, while the stiffer sensor changes only slightly. As rigidity increases, both sensors deform under axial loading, and rigidity is estimated from the ratio of their resistance changes.

Results

Bench-top testing was performed under controlled axial loading up to 2.5 N to examine the differential behaviour of the sensor pair. The measurements highlight the effect of engineered stiffness contrast under force-controlled conditions, while also confirming comparable sensor behaviour when evaluated at equal axial extensions up to 150%. Together, these observations support the use of a ratio-based metric to decouple strain sensing from mechanical stiffness.



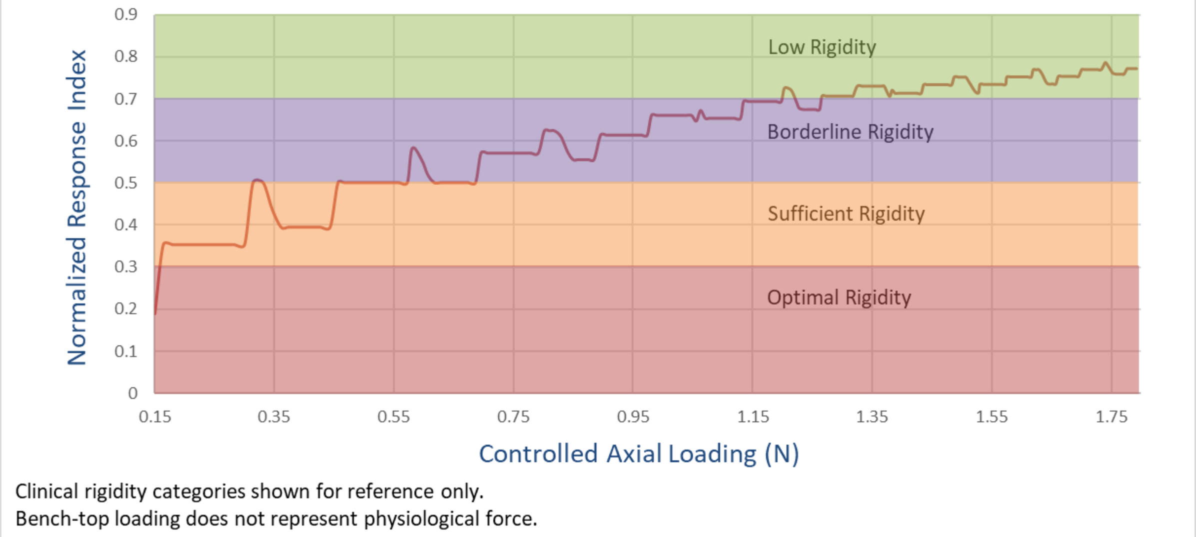
Relative resistance response of the two stretchable strain sensors under increasing axial force, showing different force response trends due to their distinct mechanical stiffness.



Relative resistance change of two stretchable strain sensors plotted against axial extension, showing comparable electromechanical response under identical strain despite differences in mechanical stiffness.

The normalized response ratio was calculated from the resistance changes of the two sensors measured under identical loading conditions. With increasing axial load, the ratio changed in a consistent and progressive manner, reflecting a shift in how deformation is shared between the sensors. This behavior demonstrates that the ratio provides a meaningful proxy for axial rigidity and can be calibrated against clinically reported rigidity references.

Rigidity Category	Force Range (N)	Interpretation
Insufficient	< 3.92	Flaccid / weak rigidity
Borderline	3.92 – 4.9	Partial rigidity, borderline ED
Sufficient	4.9 – 9.8	Functional rigidity for penetration
Optimum	> 9.8	Full rigidity / healthy function



Normalized response ratio obtained from the two sensors as a function of controlled axial loading, demonstrating a consistent trend that supports its use as an axial rigidity indicator.

Conclusion

- A soft dual-sensor design was implemented to sense axial deformation through relative electrical changes.
- Bench-top evaluation confirmed stable behavior, with distinct responses driven by differences in sensor stiffness.
- The resulting response ratio evolved consistently with axial loading, indicating its suitability as an axial rigidity proxy after clinical calibration.
- The system is currently being prepared for planned human testing to enable clinical calibration and validation.

Acknowledgements

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