

From Rigid to Flexible and Stretchable Hollow Microneedle Patches: Integrated Microfluidic Platforms for Dermal Interstitial Fluid Extraction and Intradermal Therapeutic Delivery

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Summary:

Dermal interstitial fluid is an attractive biofluid for minimally invasive and longitudinal biomarker monitoring. Here, we develop a flexible hollow microneedle patch that combines two-photon-polymerised hollow microneedles, an elastomeric backing layer, and soft microfluidic channels. Building on 3D-printed microneedles integrated with silicon microfluidics, this platform improves skin conformity while maintaining reliable dermal access. Preliminary insertion, optical, and fluidic tests demonstrate effective skin interfacing, microneedle penetration, and microchannel connectivity. This mechanically compliant approach supports wearable interstitial-fluid sampling and future closed-loop sensing systems.

Keywords: hollow microneedles, flexible patch, dermal interstitial fluid, wearable biofluid sampling, soft microfluidics.

Background, Motivation and Objective

Continuous access to physiological biomarkers is increasingly important for personalised medicine, endocrine monitoring, and closed-loop therapeutic systems. Dermal interstitial fluid has emerged as a promising alternative to blood because it contains clinically relevant small molecules and can be accessed with reduced invasiveness [1, 2]. Hollow microneedles are particularly attractive for this purpose, as they can extract interstitial fluid on demand and separate the sampling interface from the downstream sensing element [3]. Previous work demonstrated the direct two-photon-polymerisation printing of polymer hollow microneedles on silicon-based microfluidic chips, achieving mechanically robust skin insertion and in vivo interstitial-fluid extraction [4].

However, rigid chip-based microneedle platforms may have limited conformity to curved or dynamically moving skin surfaces. This can reduce interfacial stability, affect insertion reliability, and restrict long-term wearable operation. The objective of this work is therefore to develop a flexible and stretchable hollow microneedle patch that preserves the precision of 3D-printed microneedles while introducing an elastomeric skin-interfacing architecture for improved conformity and dermal access.

Description of the New Method or System

The proposed platform consists of two-photon-polymerised hollow microneedles partially embedded within a soft elastomeric backing layer and integrated with microfluidic channels for interstitial-fluid extraction and local delivery. The microneedle geometry includes a central lumen and side openings to enable fluidic access after insertion into the skin. A needle-base anchoring structure is introduced to improve mechanical retention between the printed microneedle and the soft backing layer, while reducing the risk of channel blockage during bonding.

In contrast to rigid silicon-based devices, the flexible backing layer is designed to conform to curved skin surfaces and accommodate local deformation during body movement. The soft microfluidic layer can be fabricated using mould-based soft lithography and bonded to the microneedle-bearing substrate to form a continuous fluidic pathway. This architecture decouples the requirements of the microneedle, which must be sufficiently stiff for skin insertion, from those of the patch substrate, which must be compliant for wearable skin interfacing.

Results

Preliminary fabrication demonstrates the feasibility of integrating hollow microneedles with a flexible and stretchable elastomeric microfluidic

platform. Optical inspection confirms that the hollow microneedle geometry is preserved after embedding and bonding, while the compliant backing layer allows the integrated patch to undergo bending, stretching, and twisting without visible structural failure (see Fig. 1). These deformation tests indicate that the platform can better accommodate curved and dynamically moving skin surfaces than rigid chip-based designs.

Skin-insertion tests using dye-assisted visualisation show successful microneedle penetration and local dermal access. Pre- and post-insertion imaging indicates that the microneedles remain structurally intact after insertion, supporting their suitability for repeated handling and skin interfacing. To verify the fluidic function of the integrated platform, coloured-liquid perfusion was used as a preliminary validation method. These tests confirmed continuous connectivity between the hollow microneedle lumen and the soft microfluidic channels, demonstrating the potential of the device for dermal interstitial-fluid extraction and intradermal therapeutic delivery.

Beyond fluid extraction and delivery, the microfluidic architecture provides a route for integration with downstream biosensors. By guiding extracted interstitial fluid from the hollow microneedles towards an external or embedded sensing region, the platform can decouple the skin-access interface from the sensing element. This design therefore supports future wearable systems for longitudinal biomarker monitoring, closed-loop sensing, and personalised therapeutic intervention.

Overall, this work advances hollow microneedle biofluid sampling from rigid microfluidic chips towards a conformal, mechanically compliant and biosensor-compatible wearable platform.

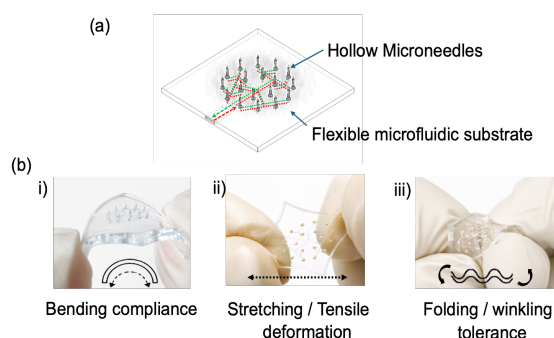


Fig. 1. Flexible and stretchable hollow microneedle patch integrated with a soft microfluidic platform. The concept combines a hollow microneedle array with a compliant microfluidic backing layer for dermal interstitial-fluid extraction and intradermal delivery. Bending, stretching, and twisting tests illustrate the mechanical compliance of the integrated patch for conformal skin interfacing.

References

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