

# Characterisation of a Monolithic 3D-Printed Tactile Sensor using a SSIM-based Analysis

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## Introduction

We introduce a monolithic 3D-printed tactile fingertip that preserves the core architecture of an established vision-based tactile sensor- skin, pins, markers, and gel - while replacing the conventional polymer melt blend gel with a soft transparent solid fabricated in a single print. This unified gel is elastic, mechanically couples all pins, and exhibits mechanical properties akin to the dermis and subcutaneous fat. Indentation experiments test the fingertip's deformation mechanism, revealing that pin length and gel thickness are critical determinants of its deformation capability. In these experiments, the structural similarity index (SSIM) is employed to evaluate and quantify the deformation of the fingertip.

## Tactile sensor Design

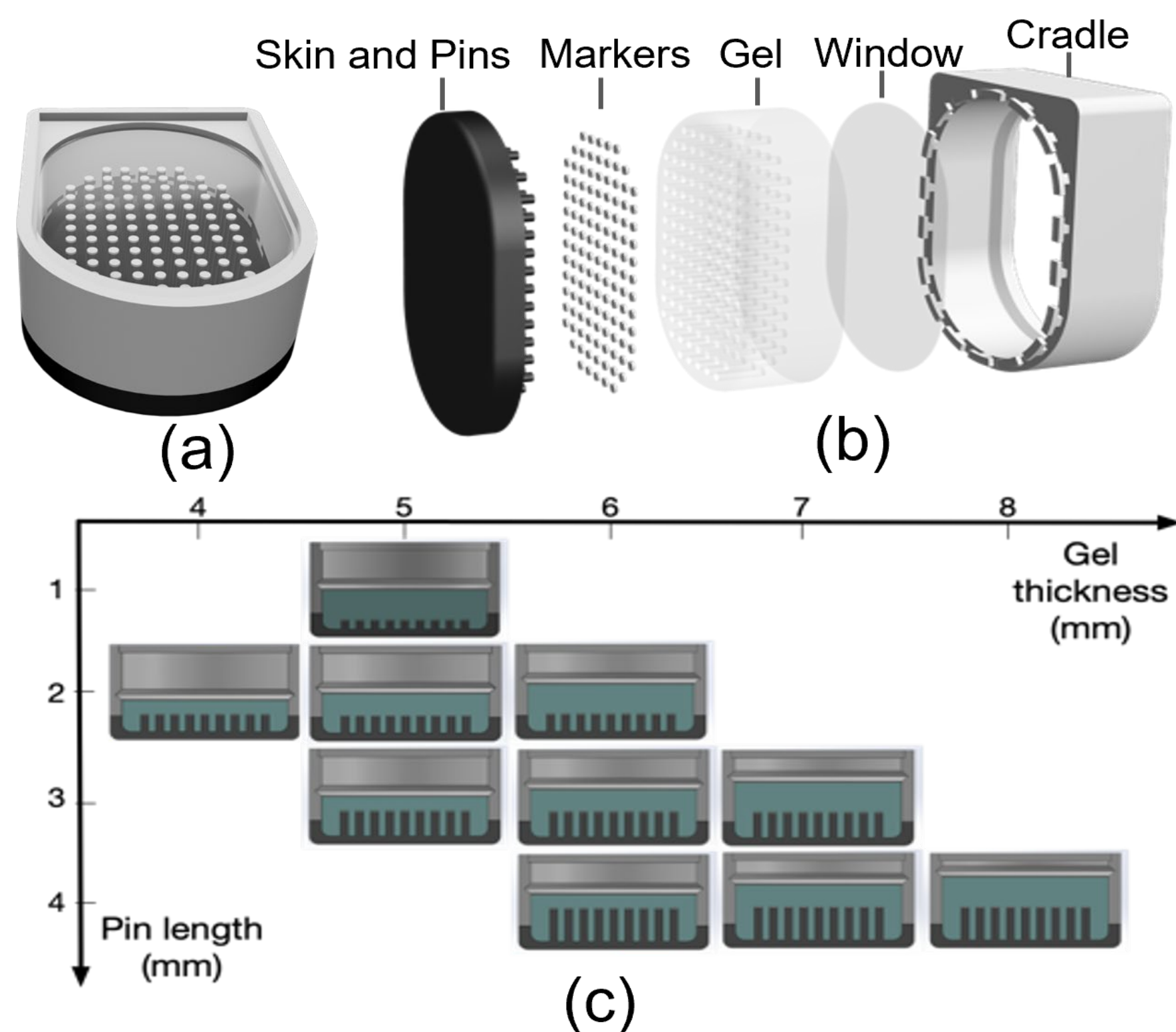


Fig. 1: (a) Assembled view showing the overall sensor geometry. (b) Exploded schematic illustrating the main components. (c) Schematic illustrations of ten sensor configurations with varying pin lengths and gel thicknesses.

## Modeling

### Double-Gaussian Model

$$SSIM(d) = A_1 e^{-\frac{d^2}{2\sigma_1^2}} + A_2 e^{-\frac{(d-\mu_2)^2}{2\sigma_2^2}} + (S_0 - A_1)$$

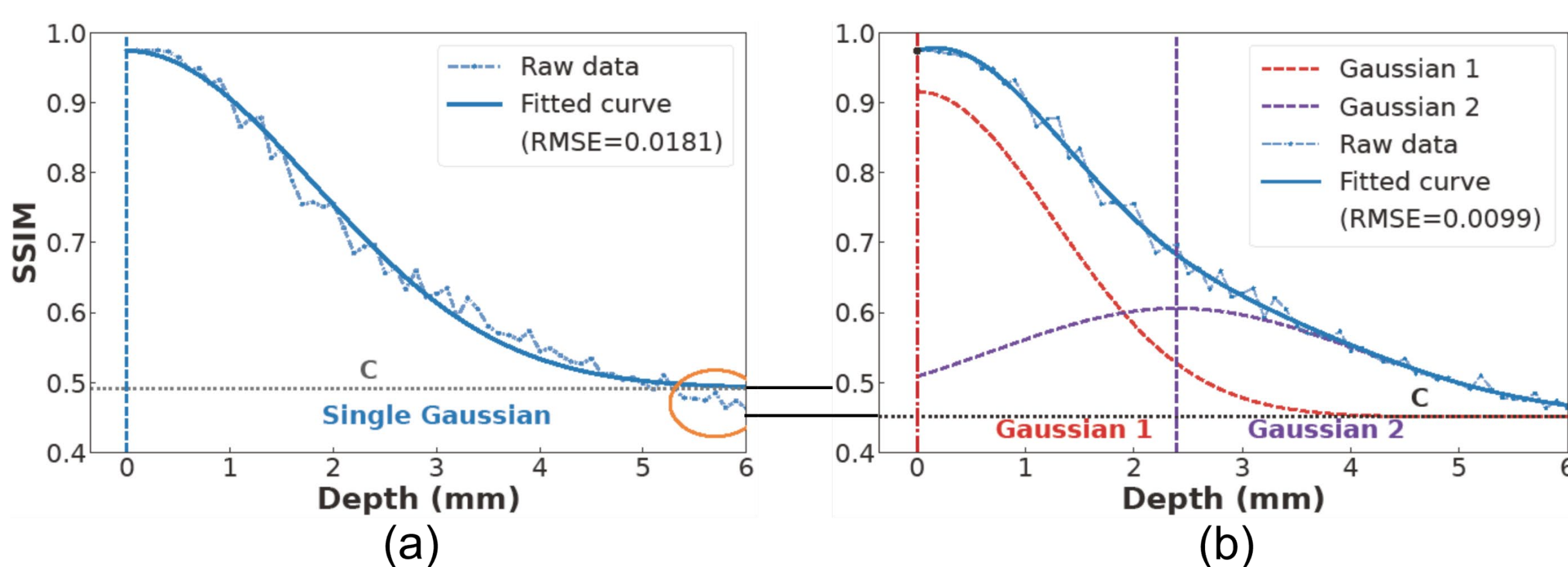


Fig. 3: Comparison and interpretation of SSIM-depth fitting models using (a) single-Gaussian and (b) double-Gaussian formulations. The single-Gaussian model captures the overall deformation trend, while the double-Gaussian model separates near-surface and deeper deformation effects.

### Refraction-aware Optical Model

#### Imaging relation

$$x_{true} = \left[ 1 - \frac{t}{L} \left( 1 - \frac{1}{n} \right) \right] x_{app}$$

#### Refraction influence factor

$$k = \frac{t}{L} \left( 1 - \frac{1}{n} \right)$$

#### Effective gel thickness

$$t = D_{gel} - L_{pin}$$

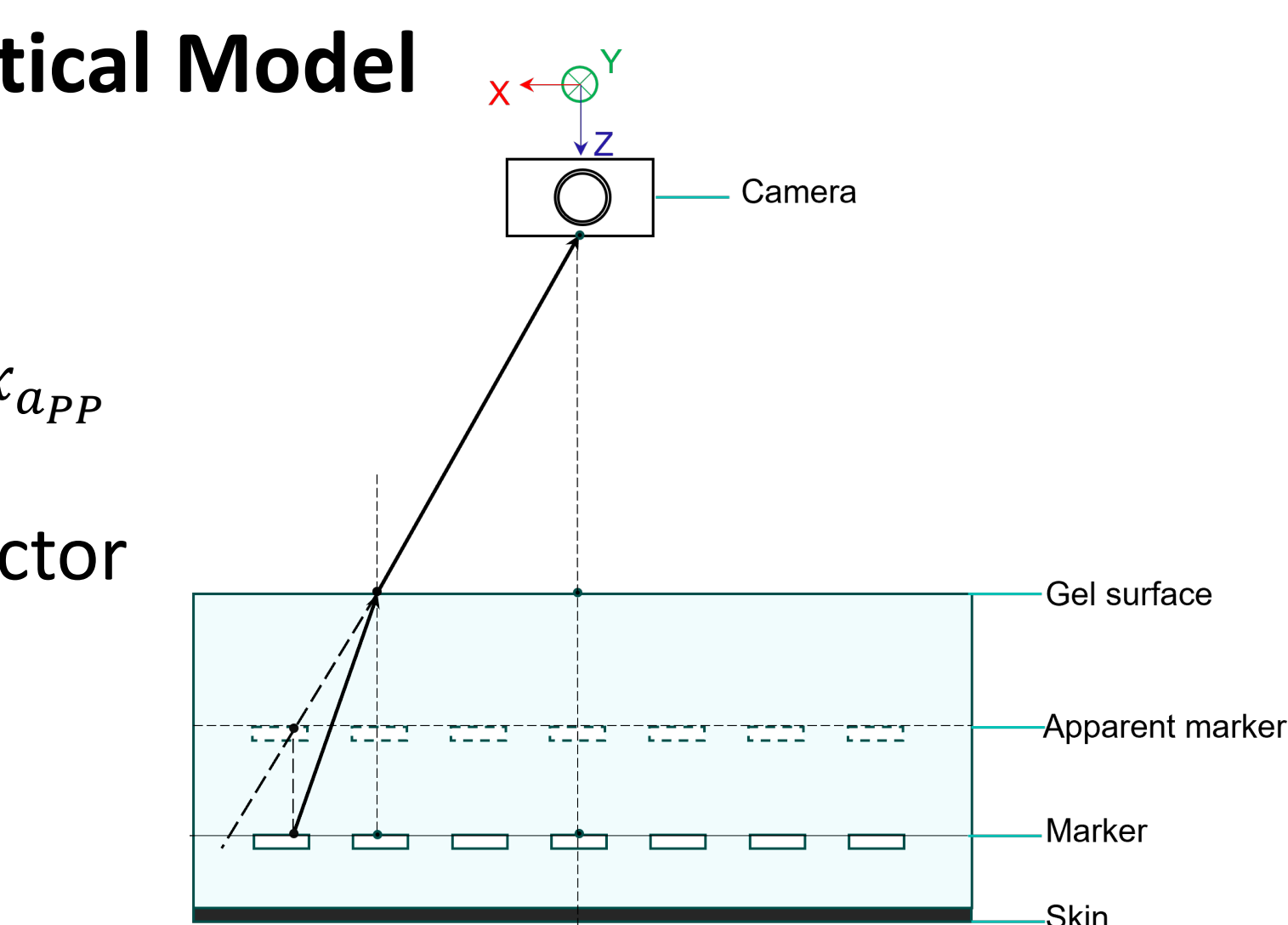


Fig. 4. Refraction modifies effective imaging geometry.

Params		Params	
A1	Near-surface amplitude	$x_{true}$	True marker position
$\sigma_1$	Near-surface deviation	$x_{app}$	Apparent marker position
$\mu_1$	Contact onset position ( $\mu_1=0$ )	L	Object distance
A2	Deep deformation contribution	n	Refractive index of the gel
$\mu_2$	Characteristic depth	$D_{gel}$	Gel thickness
$\sigma_2$	Deep deformation spread	$L_{pin}$	Pin length

## Experiments

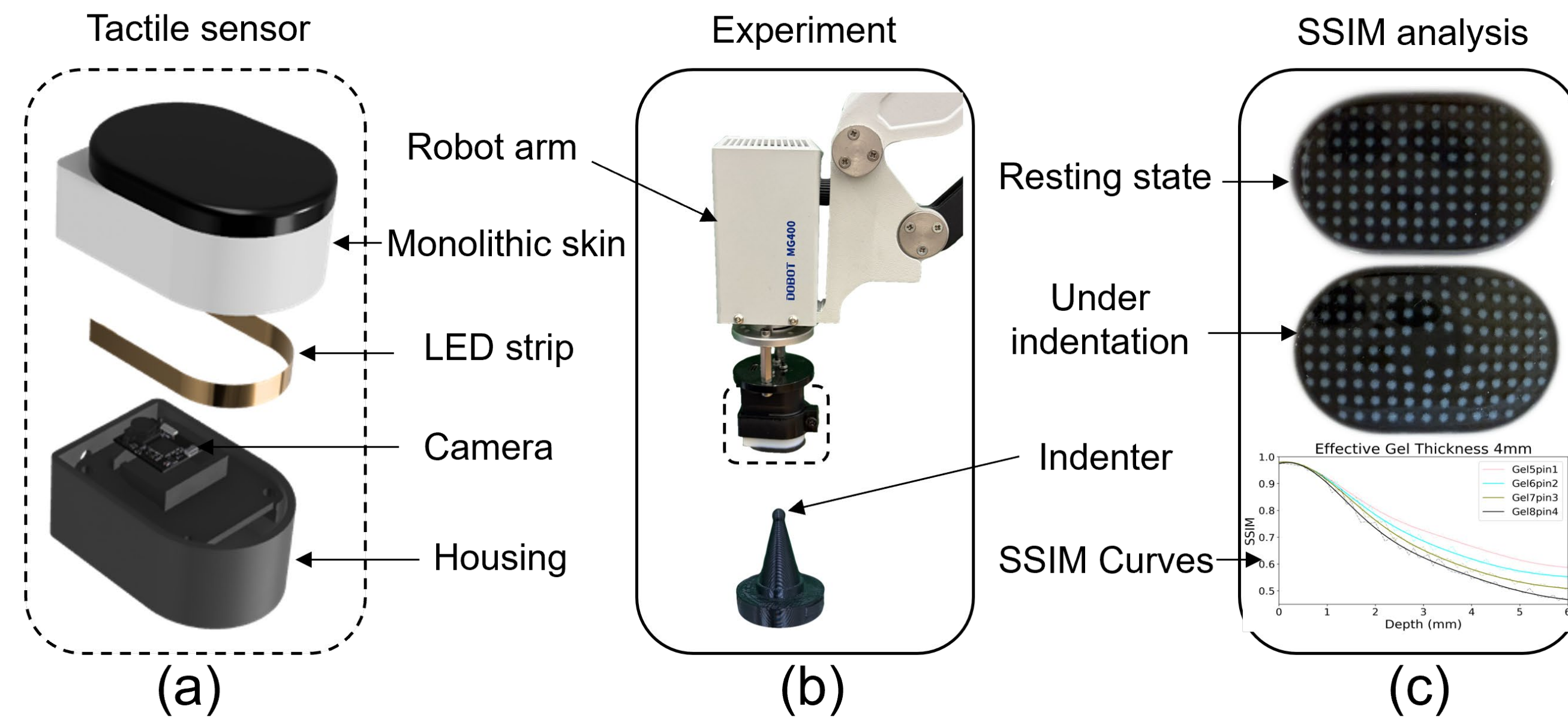


Fig. 2: (a) The proposed monolithic tactile sensor. (b) Indentation experimental setup using a sphere-tipped indenter. (c) SSIM-based image deformation quantification.

### Data Acquisition

- Dark environment
- 0.1 mm indentation increment

### Data Processing

- $SSIM(d) = SSIM(I_d, I_{ref})$
- Construct SSIM-depth curves.

## Results

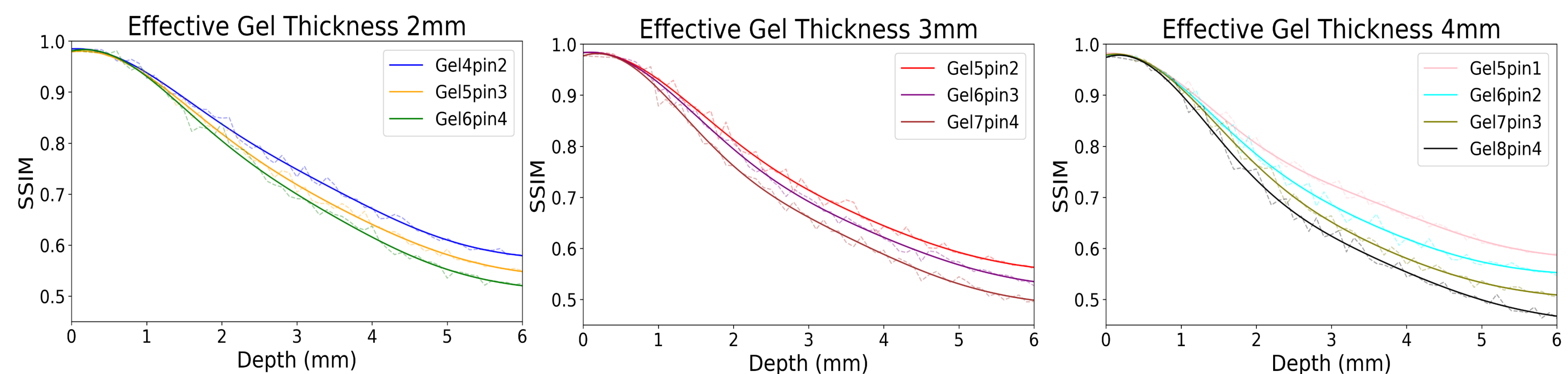


Fig. 5: SSIM-depth curves and double-Gaussian fitting results for proposed sensors with different pin lengths at three effective gel thicknesses: (a) 2 mm, (b) 3 mm, and (c) 4 mm.

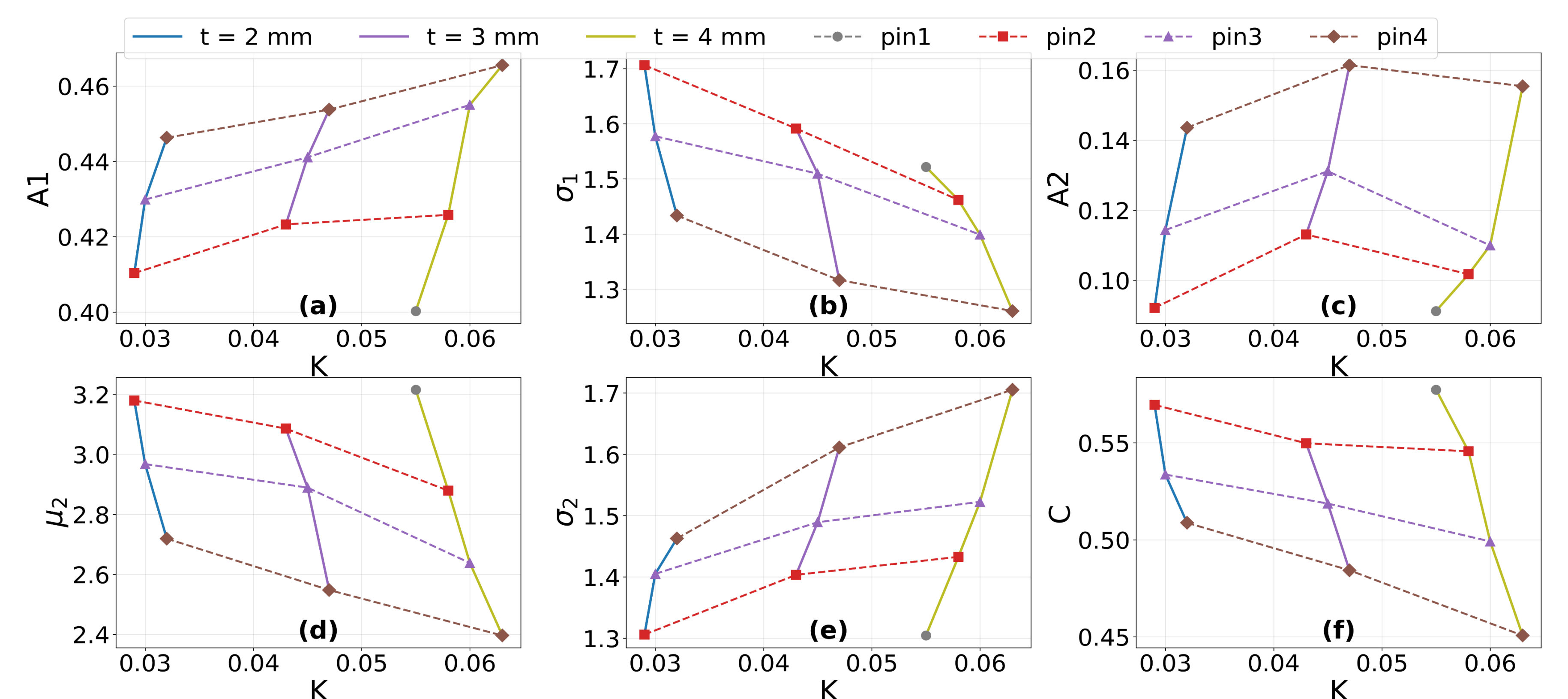


Fig. 6. Double-Gaussian Fitting Parameters with Refraction Influence Factor k for ten sensors.

- The SSIM-depth responses exhibited clear nonlinear deformation behaviour across all sensor configurations.
- The double-Gaussian model successfully captured both near-surface and deep deformation responses.
- Pin length mainly influenced SSIM through geometric deformation transmission, where longer pins produced earlier and stronger deformation responses.
- Gel thickness mainly affected SSIM through refraction-induced optical amplification, where thicker gel layers increased the apparent marker displacement and SSIM sensitivity.
- The experimental results demonstrate that geometric amplification and optical amplification jointly determine the SSIM response of the proposed tactile sensor.

## Contributions

- An SSIM-based framework is established to characterize deformation responses of vision-based tactile sensors through SSIM-depth curves.
- A monolithic 3D-printed tactile fingertip is developed using a directly printed soft transparent solid, enabling fully integrated fabrication.
- The influence of pin length and gel thickness on SSIM response is systematically analysed through two mechanisms: geometric deformation transmission and refraction-induced optical amplification.