BioTacTip: A Soft Biomimetic Optical Tactile Sensor for Efficient 3D Contact Localization and 3D Force Estimation

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***Abstract*— In this study, we introduce a new soft biomimetic optical tactile sensor based on mimicking the interlocking structure of the epidermal-dermal boundary: the BioTacTip. The primary sensing unit comprises a sharp white tip surrounded by four black cover tips that when subjected to an external force emphasizes the applied direction and contact location, for high-resolution imaging by an internal camera. The sensor design means that we can utilize the tactile images directly as the model input (not requiring marker detection) for computationally efficient reconstruction of 3D external forces, contact geometry, localization and depth, by utilizing an analytic tactile model based on dynamic friction and internal pressure. Indentation and press-and-shear tests confirmed this mechanism, with sub-mm localization and indentation errors, and normal and shear force time series that match measured quantities. The sensor design opens up a new way to instantiate biomimicry in optical tactile sensors that utilizes mechanical processing in the skin.**

I. INTRODUCTION

Human dexterity begins with our highly sensitive fingers. Of all body parts, our fingertips have the most nerves for touch [1], allowing us to feel the shape and dynamics of objects with even a light touch. Scientists studying touch in neuroscience consider the sensory mechanoreceptors near the skin's dermal-epidermal boundary [2]. Biological tactile sensitivity depends on the morphology of this boundary, where a mesh of dermal papillae and epidermal ridges amplifies small contacts via a micro-levering effect [3]. The mechanics of these skin structures transduces contact indentation and shear across a wide range of exerted frequencies

Many artificial tactile sensors have biomimetic designs based on human skin. For example, a biomimetic soft capacitive e-skin can measure normal and tangential forces because it has a 3D structure that mimics the interlocked dermis-epidermis boundary in human skin [4]. The TacTip, created at the Bristol Robotics Laboratory, is also based on the morphology of this boundary, but instead mimics the levering motion of the intermediate ridges, captured from the transverse motion of markers on the tips [5]–[7]. This transverse motion of the markers forms a representation of the skin's indentation and shear, and has been found to resemble the neural activity recorded from mechanoreceptor afferents in classic studies of skin neurophysiology [8].

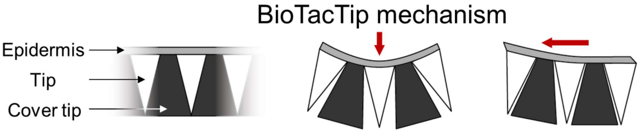

Fig. 1. Activation of the BioTacTip's primary sensing unit in response to strain: (left) at rest; (middle) under normal indentation; (right) under shear.

Another important feature of cutaneous human touch is its high spatial resolution, with 100s of mechanoreceptors per fingertip. This aspect is captured in the increasing use of optical tactile sensors having internal cameras, such as the GelSight [9], DIGIT [10] and the TacTip soft biomimetic tactile sensor described above. High-resolution depth information can be imaged from light reflected from an internal membrane [9] or with a depth camera [11]. However, skin shear is usually sensed by the transverse motion of markers, which are added to the skin underside for the GelSight [12]. Markers are fundamental to the TacTip operation and are used to sense contact depth, shear and force [7]. However, these quantities cannot be modelled easily from the marker motion, so most models use 'black-box' deep learning models trained with large data sets. These have many limitations, *e.g.* computational resources, lengthy data collection and recalibration issues if the sensor skin is changed or damaged.

In this study, we present a novel soft biomimetic tactile sensor capable of computationally efficient reconstruction of 3D forces alongside contact localization and depth, owing to its innovative sensing mechanism derived from a new biomimetic fabrication of the morphology of the epidermal-dermal boundary (Fig. 1). The primary sensing unit comprises a sharp tip surrounded by four cover tips that conceal the tip's point when at rest. When subjected to an external force, the sharp tip's movement relative to the flat cover tips is intentionally emphasized in the applied direction, for imaging by the internal camera and post-processing of the contact properties. Our main contributions are:

(1) A novel biomimetic tactile transduction mechanism: the primary sensing unit of our proposed soft biomimetic optical tactile sensor is based on the peg-like structure of the dermal-epidermal boundary, retaining the micro-levering effect while also informing directly about indentation (Fig. 1).

(2) An interpretable, analytic tactile model based on the sensor's working principle allows efficient calculation of contact shape, centre of contact localization, indentation depth, along with normal and shear forces. Each BioTacTip is usable with this model after only a simple calibration without

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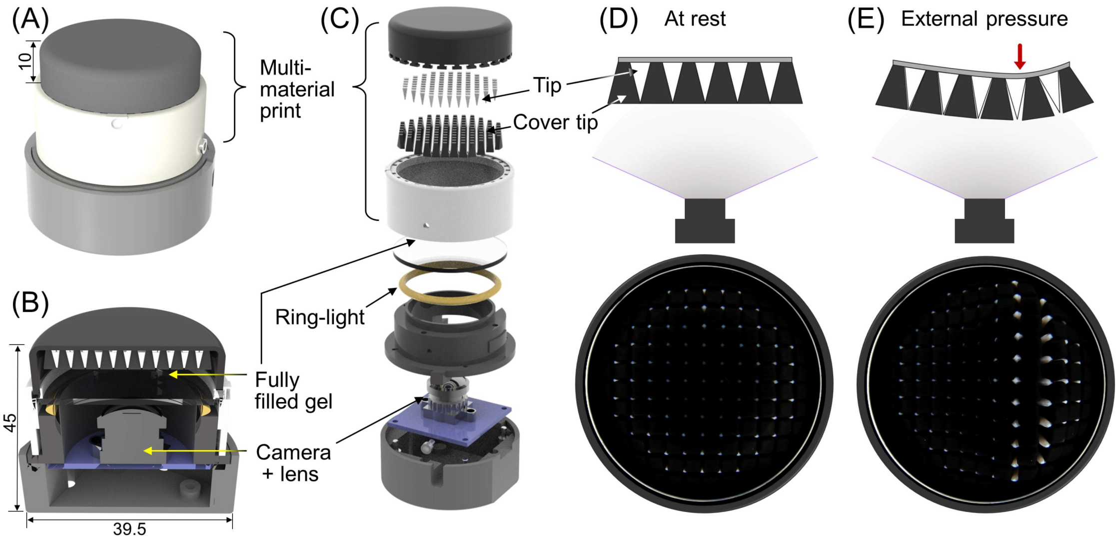

Fig. 2. (A) BioTacTip's outer appearance. (B) Cross-section view of BioTacTip. (C) Exploded view of its components. (D) The tips and cover tips in a rest state (top) and an image of this setup as captured by the camera (bottom). (E) Motion of the tips and cover tips under external pressure.

the need for extensive data acquisition and training.

(3) Our tactile model leverages processed raw images as inputs, eschewing the need for marker detection methods to enhance computational efficiency.

II. Related Work

Many artificial tactile sensors have prioritized temporal resolution over enhancing spatial resolution. For example, piezoresistive and capacitive tactile sensors [16]–[18] excel at measuring high-frequency kHz pressure distributions during contact, but face challenges in measuring shear and give a low-resolution spatial output. Further, piezoresistive and capacitive tactile sensors do not have the spatial recognition capabilities compared to vision-based tactile sensors (VBTS) [9], [10], [13], [19], such as recognizing the texture features of an object' surface (see comparison in Table I).

Advancements in miniature camera technology and the use of soft material manufacturing have given prominence to VBTS. These sensors can have high spatial resolution due to their use of MegaPixel arrays, while their temporal resolution is typically 30-120 frames per second (although faster cameras or event-based technology [20] are being explored). Familiar examples include MIT's GelSight [9], Meta's DIGIT [10] and BRL's TacTip [6], [7], [21].

The GelSight and DIGIT determine contact conditions revealed from the shading due to three RGB light sources reflected from an outer membrane. For a thin membrane over a stiff elastomer, these sensors can give highly-detailed measurements of indentation, but are insensitive to shear. Therefore, to improve shear and contact force estimation, they incorporate thin marker arrays within the sensor layer [12].

TABLE I

Tactile Sensor Comparison

Sensor	Common Technologies	Localization MAE (mm)	Indentation MAE (mm)	Normal Force MAE (N)	Shear Force MAE (N)	Texture Recognition	Setup Difficulty
BioTacTip*	**Interpretable model**	$\lesssim 0.50$	$\lesssim 0.50$	$\lesssim 0.20$	$\lesssim 0.20$	**Medium**	**Low**
Digit* [10]	Neural network	$\lesssim 0.19$	$\lesssim 0.22$	None	None	High	Medium -high
9DTact* [13]	Neural network	$\lesssim 0.05$	$\lesssim 0.05$	$\lesssim 0.31$	$\lesssim 0.31$	Medium -high	High
TacTip* [14]	Neural network/ blob detection + mapping model	$\lesssim 0.16$	$\lesssim 0.20$	None	None	Low	Medium
GelSlim2.0* [15]	Finite element method + mapping model	None	None	$\lesssim 0.32$	$\lesssim 0.22$	High	High

In contrast, TacTip can simultaneously assess the external shape and estimate contact force using an array of markers on the tips of pin-like papillae beneath its sensing surface [6], [7]. Tips perpendicular to the sensing surface move as the surface deforms, which an internal camera captures over time. Typically, a trained neural network estimates the external contact conditions from the movement of the tip array [22]. This estimation is also utilized for pose and shear estimation, enabling tactile servoing [23].

For soft optical tactile sensors, the absence of a comprehensive and interpretable dynamic model to predict the contact properties and force has encouraged the use of deep neural networks trained on very large datasets of tactile images (*e.g.* [13], [14]). This has led to much progress in tactile perception and control, but also has costs in computational efficiency and the extensive data gathering for model training. We have included an assessment of setup difficulty, which encompasses both the time investment and the challenges involved in data collection or calibration (comparison in Table I). Sim-to-real is one way to limit data collection in the real world, for example using an Elastomer Deformation Simulator such as Tacchi [24] to generate data to pretrain a model; however, so far there remains a Sim2Real gap that is addressed by gathering real data for further model training. In particular, due to these sensors' manufacturing complexity, such as using casting and demolding to produce the skin of the DIGIT and injecting gel to fill the skin of the TacTip, these models may not generalize well across fabricated sensors. Thus, there is a need for a high-resolution soft tactile sensor that can efficiently acquire contact information such as location, indentation, normal force and shear force directly from the tactile image.

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