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Cost-Efficient Flexible Supercapacitive Tactile Sensor With Superior Sensitivity and High Spatial Resolution for Human-Robot Interaction

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ABSTRACT Tactile sensing is crucial for the safety, accuracy and robustness of the human-robot interactions in the fields of wearable equipment, service robots and healthcare robots. Although many efforts have been made, it still requires much work to develop functional and reliable flexible tactile sensors with superior sensitivity, wide measurement range, high spatial resolution and low cost based on simple structures and easy fabrication. Here, this paper introduces a flexible supercapacitive tactile sensor with outstanding and balanced performance. The tactile sensor contains two layers of flexible electrodes and a layer of ionic-gel coated microfiber matrix to form a supercapacitive sensing structure. The flexible electrodes and the ionic microfiber matrix are processed with scalable techniques such as screen printing and gel-coating, which guarantee the ultra-flexibility and low fabrication cost. The experimental data suggests strong linearity in the pressure-capacitance relationship and high sensitivity (135.9 nF$\cdot$kPa$^{-1}\cdot$cm^2 or 27.11 kPa^{-1}). Wide pressure measurement range (from 0 kPa to 1200 kPa) is also achieved by balancing structure parameters. Dynamic responses of the tactile sensors could accurately reflect the applied pressure cycles from human-finger tapping and machine pressing. The tactile sensor can map the pressure distribution with a high spatial resolution (>2 points$\cdot$mm^{-2}) when connected with the specially designed electric circuitry. The spatial resolution from sub-mm to large area makes it promising for various sensing applications in human-robot interactions, from finger touch to body contact. The developed tactile sensor in this study owns superior applicability and universality which makes it a trustworthy candidate to benefit various applications in robotics, flexible electronics and bioengineered equipment.

INDEX TERMS Human-robot interaction, supercapacitive, tactile sensor.

I. INTRODUCTION

With the rapid advancement of robotics and artificial intelligence, both academia and industry are longing for the innovative wearable equipment, service robots and healthcare robots that can sense human intention and provide physical assistance in various surroundings. Visual and audio sensors have been widely applied in the field for these purposes. However, the visual or the audio sensing can hardly describe all the information details of the physical contact during the human-robot interactions when happens in close proximity. In these scenarios, the tactile sensory owns great significance, sometimes the irreplaceable access, for intelligent robots to feel the contact, to recognize human intention

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and to obtain the surrounding environmental information [1]. For the human-robot interactive robotic systems, the flexible tactile sensors are essential to acquire the necessary tactile information to guarantee the operation safety and the comfortability from the physical contact. Hence, the advances of innovative and reliable flexible tactile sensing systems are not only of great interest in the field of flexible electronics [2], [3], but also with fundamental importance for human-robot interaction studies [1], [4], [5]. Various kinds of flexible tactile sensors, based on the working principles of piezoresistance [6], [7], piezoelectricity [8], field-effect transistors [9]–[11], capacitance [12] have been widely studied, and many of them own superior performance parameters. However, very few of them have been applied to the human-robot interactive systems to solve real-world issues. The primary reason is that the practical applications of the tactile sensing systems require superior and balanced combined properties, rather than the excellence in a single specification parameter without considering the sensing system as a functional unity.

Firstly, the cost-efficiency should be considered equally important with other key performance parameters, such as the sensitivity, spatial resolution and effective measurement area [13]. Being fabricated with microfabrication or electrostatic spinning, some of the tactile sensors could obtain extremely high-pressure sensitivity or spatial resolution. However, it would be more than costly when these materials and fabrication protocols are employed in the large-scale production of the sensors [14], [15]. Innovative and functional materials with commonly used manufacture techniques should be prioritized for further considerations.

Secondly, the wide measurement range and intrinsic flexibility are required to employ the tactile sensors into human-robot interaction systems [15], [16]. The intrinsic flexibility is one of the ultimate goals for the tactile sensors where contact comfortability and safety are of great importance [17]. The sensors that own a wide measurement range could potentially enlarge the potential application fields and decrease the user expenses of sensor purchases for different ranges. Both wide measurement range and high flexibility require innovative material fabrication and device assembly methods.

Still, the tactile sensors need to be further optimized to balance the spatial resolution and the measurement area. Arrays of sensing units are the commonly used formation to gauge the tactile information distribution (the normal pressure, shear, etc.), and pursuing high spatial resolution of measurement in a large target area would lead to connection wiring issues [6], [7], [18]. Although the microstructure-dependent capacitive sensor arrays and the field-effect transistors could minimize the wiring numbers by using crossing electrode arrangement, the dependent fabrication methods are still inferior to meet the requirement of both large measurement area and high spatial resolution at the same time of using a cost-efficient manner [9], [19], [20].

Furthermore, the ability of anti-interference needs to be further improved, especially for the capacitive tactile sensors. Capacitive tactile sensors are highly sensitive and relatively easy to form arrays with a high spatial resolution [14], [15]. However, due to the small capacitance induced by the mechanism of accumulating static charges, the conventional parallel-plate capacitive sensors with high spatial resolution are vulnerable to environmental interference and capacitive coupling effects.

Therefore, there is still lot to do to balance the flexibility, spatial resolution, measurement range, cost and fabrication complexity at the same time of pursuing excellence in performance characteristics.

Here, confronting the mentioned issues and challenges, this paper introduces a new type of flexible supercapacitive tactile sensor. Supercapacitive sensing units are employed into the tactile sensor, which guarantees the superior sensitivity, high anti-interference ability and robustness. Universal and scalable manufacturing techniques, such as screen-printing and gel-coating, are used to fabricate and to assemble the sensors, which further enhance the uniformity of the materials as well as the sensor performance. The silver-nanoparticle based flexible conductive electrodes and ionic-gel based microfiber matrix, as the primary materials to construct the ultra-thin and flexible tactile sensor, owns advantages of low cost and simple processing protocols that ultimately shrink the sensor material cost into 1 $ per piece (for 1 mm spacing between 1 mm-wide electrodes and 20×20, row by column, capacitive sensing units). Pressure distributions under different test conditions are mapped to demonstrate the applicability and universality of the work. The developed tactile sensor is potentially beneficial for various scenarios where physical human-robot interaction is critical, such as service robot, healthcare robot and wearable equipment.

II. STRUCTURES AND WORKING PRINCIPLES

The flexible tactile sensor consists of three layers, the top and bottom electrode layers, and the ionic-gel coated microfiber matrix in the middle, as illustrated in Fig. 1. Both the top and the bottom microelectrode layers are fabricated by screen-printing silver nanoparticle-based conductive ink onto flexible Polyurethane (PU) membranes, as demonstrated in Fig. 1(c). The middle layer of the ionic matrix was fabricated by coating ionic-gel (H_3PO_4-PVA) to a microfiber sheet (Polypropylene, or nonwoven fabrics, thickness: $\sim$0.24 to $\sim$0.72 mm, depending on the number of layers, see more in the supplementary document), as shown in Fig. 1(d). As demonstrated in Fig. 1(e), the top and the bottom layers are assembled in the crossing pattern to sandwich the ionic matrix to form supercapacitive units. The direct contact between the flexible electrodes and the ionic microfiber matrix leads to the formation of the electrostatic double-layer capacitors (EDLCs, a type of supercapacitor) at the contact interfaces, as illustrated in Fig. 2.

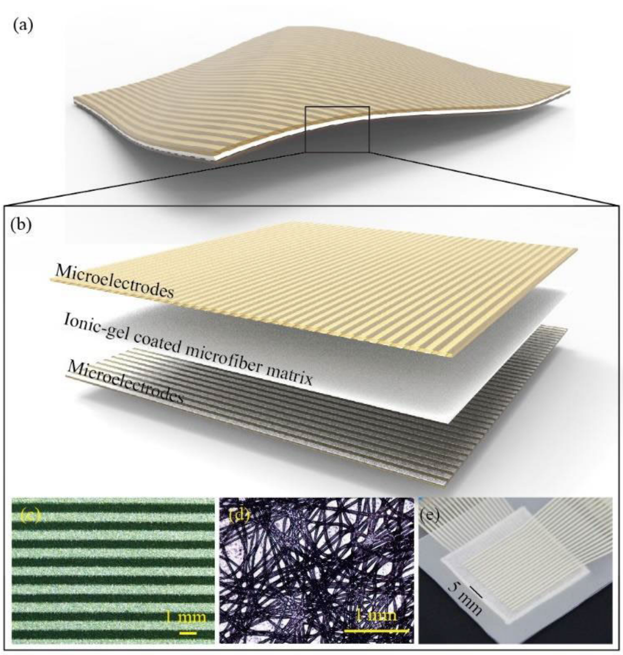

FIGURE 1. **The flexible supercapacitive tactile sensor (a) and (b) Schematics of the tactile sensor. (c) A microscopic picture of the screen-printed electrodes. (d) A microscopic picture of the ionic-gel coated microfibers matrix. (c) An assembled tactile sensor with sub-mm spatial resolution.**

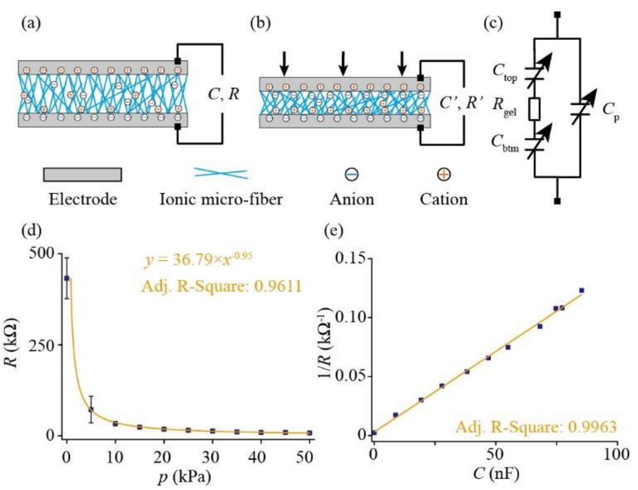

FIGURE 2. **The working principle of the supercapacitive tactile sensor (a) and (b) The EDLC variation during the deformation of the tactile sensor. (c) The analogic circuit of the EDLC sensor. (d) The relationship between the electric resistance *R* and the applied pressure *p*, which could be fitted close into a hyperbola function format. It further suggests a linear-ish relationship between the p and the 1/*R*. (e) The linear relationship between the total capacitance *C* and the inverse of the electric resistance *R* with curve fitting.**

In general, the capacitive pressure sensors follow the basic electric principle of capacitance, as

$$C = \varepsilon \frac{A}{d} \tag{1}$$

where C is the capacitance, F; ε is the permittivity of the dielectric layer or the ionic-gel membrane, F/m; A is the area of overlap of the two plates in parallel-plate capacitor or the area of the electrostatic double-layer in EDLCs, m^2; d is the distance between the electrode plates or the thickness of the Helmholtz layer in EDLCs, m.

The traditional parallel-plate type capacitive pressure sensors mostly depend on the capacitance variation due to the change of the distance d or overlap area A under the applied load. The electrode dimension and the thickness of the dielectric layer have a significant influence on the sensitivity and robustness of the pressure measurement. Different strategies have been applied to enhance the sensitivity by increasing the overlap area A with additional microstructures or decreasing the distance between the electrode plates d [21]. However, due to the inherent limitation of the working principle, most of the improvement strategies would introduce extra cost or complicate fabrication protocols or other uncertainties to the pressure sensors, without fundamentally increasing the spatial sensitivity or enhancing anti-interference ability. The essential reason is that the total capacitance of each unit of the parallel-plate capacitive sensors is relatively small and hence vulnerable to the interferences from the environment and the human body.

In the EDLCs, the characteristic thickness of the double layer is the Debye length, which is several angstroms and believed not variable to the exerted pressure. Therefore, the EDLC units typically own much higher capacitance compared with the parallel-plate capacitors when in the same dimensions or structures [22]. Owing to the larger capacitance of each sensing unit/point, the employment of the EDLC structures can significantly enhance the anti-interference capability at the same time of improving the structural flexibility and simplifying the electric measuring circuits [15], [23], [24]. Another advantage of the high anti-interference ability of the EDLC structures is that the dimension of the crossing-electrodes could be significantly scaled down to increase the spatial resolution using commonly used scalable fabrication techniques in large-area of flexible substrates.

For the supercapacitive tactile sensor, the contact area A between the flexible electrodes and the ionic-gel microfibers, in which the electrostatic double layers form, is the major influencing parameter, as illustrated in Fig. 2. When applying pressure onto the flexible sensor, the middle layer of the ionic matrix is compressed to increase the interface area between the electrodes and the ionic-gel micro-fibers, as well as the internal contact within the fibrous membrane. As a result, the capacitance increases under external pressure, as illustrated in Fig. 2(a) and 2(b). The analogical circuit of the tactile sensor is illustrated in Fig. 2(c). C_{top} and C_{btm} are the capacitance of the EDLCs of the two interfaces. C_p is the capacitance due to the electrode coupling, which is much smaller than C_{top} and C_{btm}. R_{gel} is the electric resistance of the ionic gel membrane. Fig. 2(d) plots the data of the electric resistance R of the tactile sensor during the variation of the applied pressure p. The experimental data and the fitted curve indicate that the electric resistance R of the tactile sensor is approximately proportional to the reciprocal of the applied

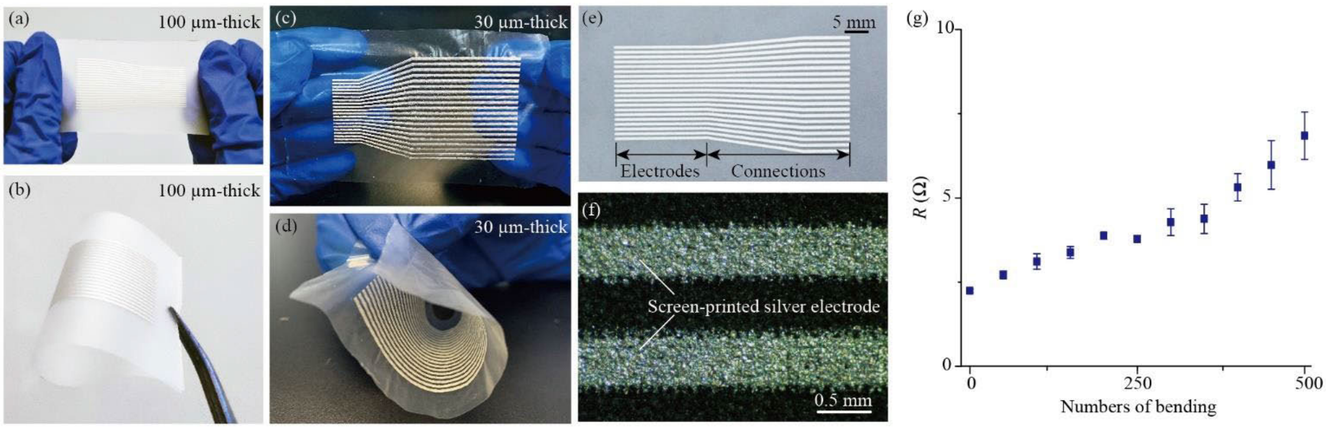

FIGURE 3. The manually screen-printed microelectrodes. (a) and (b) Fabricated electrodes using 0.1 mm-thick PU membranes. (c) and (d) Fabricated electrodes using 0.03 mm-thick PU membranes. (e) Electrode sections and the connection sections. (f) Microscopic observation of the printed electrodes. (g) The conductivity measurement of the printed microelectrodes after 500 times of repeated 180° device bending.

pressure p. The reason for the decrease of the electric resistance under pressure is due to ionic matrix compression that increases the internal contact and the interface area between the electrodes and the ionic-gel micro-fibers. It ultimately increases the conductivity of the device (see more details in the supplementary document).

Fig. 2(e) further demonstrates the linear relationship between the total capacitance C and the reciprocal of the electric resistance R ($1/R$) during the tactile sensor operations. Since the variable of area A is dominating in (1) that describes the EDLC variation, Fig. 2(d) and 2(e) validate that the capacitance of the EDLCs (C_{top} and C_{btm}) is proportional to the contact area A between the electrode and the ionic microfiber matrix.

III. MATERIALS AND FABRICATION

The flexible tactile sensor consists of three layers of ultrathin membrane materials: two layers of flexible electrodes and a layer of ionic microfiber matrix, and they are fabricated with simple protocols using scalable techniques such as screen-printing and gel coating.

A. SCREEN-PRINTED FLEXIBLE MICROELECTRODES

Flexible and conductive electrode fabrication has been widely studied, and various approaches have been developed [15], [16], [24]–[26]. Among them, the screen-printing is the most mature conventional printing technique on flexible substrates. Also, in the flexible tactile sensor fabrication, the essential work is to generally balance the device flexibility, sensitivity, spatial resolution, measurement range and cost-efficiency, rather than pursuing only one or few attractive parameters. Both the top and the bottom electrodes are screen-printed using silver-nanoparticle based conductive ink on flexible Polyurethane substrates (Silver conductive ink, XTGO-2, Deyang Carbonene, China). During the assembly, the electrodes are crossing-layout to sandwich the ionic microfiber matrix to form EDLC pressure sensing unit arrays, as shown below in Fig. 1 and Fig. 3.

With the screen-printing process, the maximum spatial resolution could be optimized into the range of 0.03 mm to 0.1 mm [27]–[30]. To considering the practical demands for tactile sensing for human-robot interaction applications, the spatial resolution of the crossing electrodes was set in the range of sub-mm in this study. Fig. 3 demonstrates the printed flexible microelectrodes and the conductivity measurement after repeated device bending test (see details in the supplementary document). Fig. 3(a) and 3(b) demonstrate superior flexibility of the manually printed electrodes using 0.1 mm-thick PU substrate, and the same protocols are feasible to the ultrathin 0.03 mm-thick substrate, as in Fig. 3(c) and 3(d). In each of the printed electrodes, there are two sections, the electrode section and the connection section. The electrode section is to make contact with the ionic microfiber matrix to form EDLCs, and the connection section is to connect the peripheral measurement electronic circuitries. The dimensions (electrode width-space) of the demonstrated microelectrodes are 0.5 mm-0.5 mm in Fig. 3. Fig. 3(f) is the microscopic observation of the electrodes, and it suggests that silver-NP ink is well coated onto the PU substrate. Repeated bending experiments of the assembled tactile sensor were employed to test the robustness of the electrode fabrication, and the data is plotted in Fig. 3(g). Different experimenters operated the bending tests manually, during which the minimal radius curvature was about 5 mm to 10 mm (see details in supplementary documents). Fig. 3(g) plots the conductivity variation of the fabricated silver ink electrodes during the bending tests of assembled sensors, and the measurement data prove that the flexible microelectrodes own robustness after 500 times of 180° device bending, although the electric resistance slightly increases and deviation exists. Higher robustness and uniformity could be expected when the screen-printing machine replaces the manual operation and parameters of printing protocols are optimized (see more in the supplementary document). The effective area of a single process of screen-printing is about 600 mm◊400 mm. The measurement area could be larger than 400 mm × 400 mm

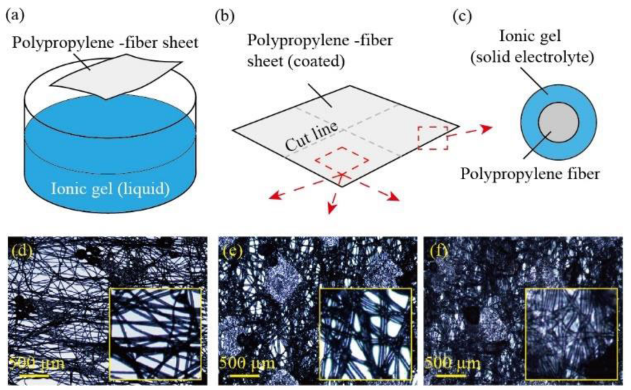

FIGURE 4. The fabrication of the ionic-gel coated microfiber matrix. (a) to (c) Schematics of the protocols. (d) to (f) Uncoated microfiber sheet, single-layer and double-layer of the coated microfiber sheets. In the characterizations, only the single-layer of ionic microfiber membrane was used to assemble the sensors.

(without splicing) in this study if considering the connector part.

B. GEL-COATED IONIC MICROFIBER MATRIX

The essential advantage of the flexible tactile sensor in this paper over the conventional capacitive sensors is the high capacitance of the EDLCs sensing units. The fabrication of the gel-coated ionic microfiber matrix is of great significance to achieve flexible and uniform contact interfaces for each of the EDLC sensing units. Different strategies have been developed to fabricate the ionic-gel based fabric structures for a similar purpose, yet these protocols require either expensive but low-throughput equipment or costly ionic gel solutions [15], [25]. In this paper, a simple but useful protocol of ionic microfiber matrix fabrication is tested to enhance both cost- and time-efficiency, as illustrated in Fig. 4. The Polypropylene-fiber membrane, as known as non-woven fabrics, is coated with ionic gel to work as the ionic microfiber matrix in the sensor. The ionic matrix deforms under the applied pressure load, and therefore the contact area of the electrode-ionic matrix increases which directly leads to the variation of the capacitance of the sensing units.

The Polypropylene-fiber sheet (8 g/m^2 or mentioned otherwise) was cleaned and dipped into the liquid H_3PO_4-PVA (5% w/w) ionic-gel solution to wet and to coat the microfibers. After dried, the coated sheet was cut into smaller pieces to assemble the tactile sensor. As shown in Fig. 4(d) to 4(f), the uncoated and the coated (single-layer and double-layer) microfiber sheets were observed under the microscopic separately. It is clear to distinguish the difference between the uncoated and coated microfiber membrane (single-layer), based on the illustrated figure insets. The solidified ionic-gel coating, as the transparent layer around the micro-fibers, could be observed in Fig. 4(e) and 4(f), and the uniformity of the micro-fibers could guarantee the consistency of the EDLC formation at the interface. During the performance characterizations, only the membrane with single-layer of the ionic microfiber was used in the tactile sensors.

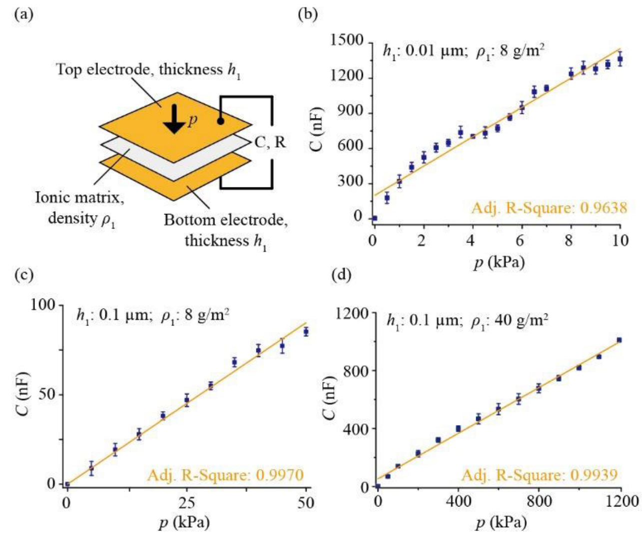

FIGURE 5. Static characteristic of the supercapacitive tactile sensor (a) Schematic illustration for static characterization tests. (b) Measurement range from 0 to 10 kPa with ultrathin ionic microfiber matrix. (c) Measurement range from 0 to 50 kPa. (d) Measurement range from 0 to 1200 kPa with thick ionic microfiber matrix. The data were obtained from repeated experiments, using the sensor arrays (1 mm spacing between 1 mm-wide electrodes and 20 × 20 capacitive sensing units).

IV. CHARACTERIZATIONS

To validate the working principles and to characterize the developed tactile sensor under static and dynamic pressure load, the test prototypes are fabricated and assembled as mentioned above. Two layers of screen-printed flexible electrodes were layout as the top and bottom electrodes, and the ionic-gel coated microfiber matrix was sandwiched in the middle. The pressure was applied using the press machine (Press head is 10 mm × 10 mm, ZQ-21B-1, Zhiqu, China), and the capacitance of the sensor is measured using an LCR meter (LCR-6300, GW Instek, China).

A. STATIC CHARACTERIZATIONS

Experimental data of static characterizations of the assembled tactile sensors are plotted in Fig. 5. During the static characterizations, different pressure ranges of 10 kPa, 50 kPa and 1200 kPa, were considered based on the used device materials. It was found that in either of the measurement ranges, the pressure-total capacitance (p-C) relationship demonstrated strong linearity. Theoretically, the coupling capacitance due to the overlapped electrodes influences the measured total capacitance, but it is ignored here in the characterization since the coupling capacitance is much smaller (in the scale of tens of pF) than the total capacitance of formed EDLCs (in the scale of nF or larger). Fig. 5(b) illustrates the pressure-capacitance relationship of the tactile

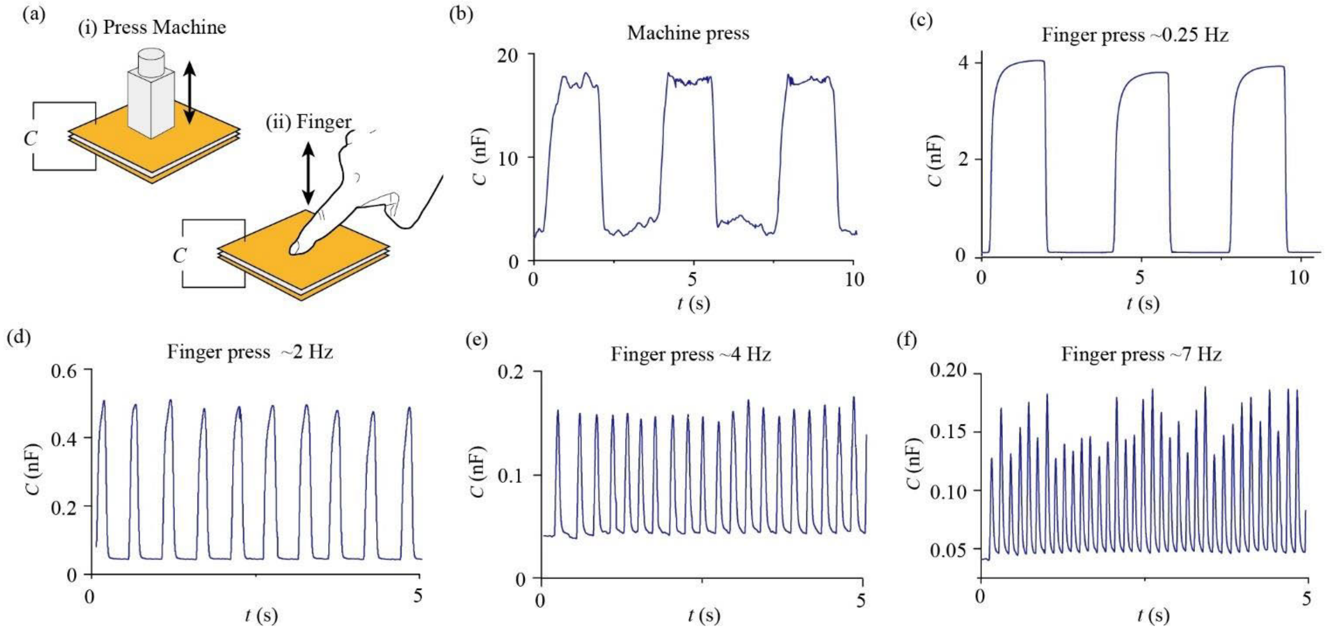

FIGURE 6. Dynamic characteristic of the supercapacitive tactile sensor (a) Schematics of the pressure load by a press machine or human-fingers. (b) to (f) The dynamic response of the tactile sensor using different pressure load cycles. The data were obtained from repeated experiments, using the sensor arrays (1 mm spacing between 1 mm-wide electrodes and 20 × 20 capacitive sensing units).

sensors using ultrathin electrode layers (0.01 mm thick) in the smaller pressure range (0 kPa to 10 kPa). The data indicates a high-pressure sensitivity of 135.9 $nF \cdot kPa^{-1} \cdot cm^2$ or 27.11 kPa^{-1}, and it is much higher than the existing supercapacitive tactile sensors [15], [25]. Fig. 5(c) and 5(d) are the experimental data when in the pressure range of 50 kPa and 1200 kPa, with ionic microfibers of different thicknesses. Especially, when a layer of thick ionic microfiber matrix was used in the tactile sensor, the pressure measurement range could reach about 1200 kPa, without damaging the linearity or the repeatability of the sensing characteristics.

The static characterizations demonstrate strong linearity, high sensitivity and wide measurement range of the developed flexible supercapacitive tactile sensors. The linear relationship between the pressure load and the capacitance variation would significantly simplify the tactile sensor calibration, the signal conditioning and post-processing, etc. The high sensitivity and wide measurement range would significantly enhance the applicability and the universality of the tactile sensing systems.

B. RESPONSE UNDER DYNAMIC PRESSURE

The dynamic characterization of the supercapacitive tactile sensor is demonstrated in Fig. 6. Pressure load cycles have been applied to the sensor to test the dynamic response, using the press machine or human fingers separately. As illustrated in Fig. 6(b) and 6(c), the response of the tactile sensor was different between using a press machine or human fingers as the source of the pressure load cycles. Both of the pressure cycles were about 0.25 Hz, but the signal response data curves using pressure machine were sharper comparing with the data curves using human fingers. The gradual changes of the capacitance when using the human fingers as pressure load are assumed as the results of the viscoelasticity behavior of both of the sensor materials and the human skin [31], [32]. The viscous component of both of the tactile sensor and the human finger generated nonlinear responses to the contact pressure, which further leads to delay (or gradual change) of the mechanical deformation as well as the capacitance variation, as depicted in Fig. 6(c). Fig. 6(d) to 6(f) are the experimental data using the human finger as the periodic pressure load to the tactile sensors, with different load frequencies. The tactile sensor could well reflect the applied pressure variation using fingers. The frequencies of the hand-actuated pressure cycles are ∼0.25 Hz, ∼2 Hz, ∼4 Hz and ∼7 Hz after calculation (typical tests selected among the repeated tapping test data). The viscoelastic effect of the flexible tactile sensor is under further studies. Signal noises were found in the tests using the press machine, and it is believed due to the vibration during the test head-sensor contact. There was no noise observed during the finger-tapping tests because that the viscoelasticity of the human fingers filtered observable vibrations during the contact (see details in the supplementary document).

C. SENSOR ARRAY FOR PRESSURE DISTRIBUTION MAPPING

Besides the pressure variation, the spatial distribution of the applied pressure load is another critical performance characteristic during the tactile sensing process. Another essential part of the work is to build an electronic circuit for the

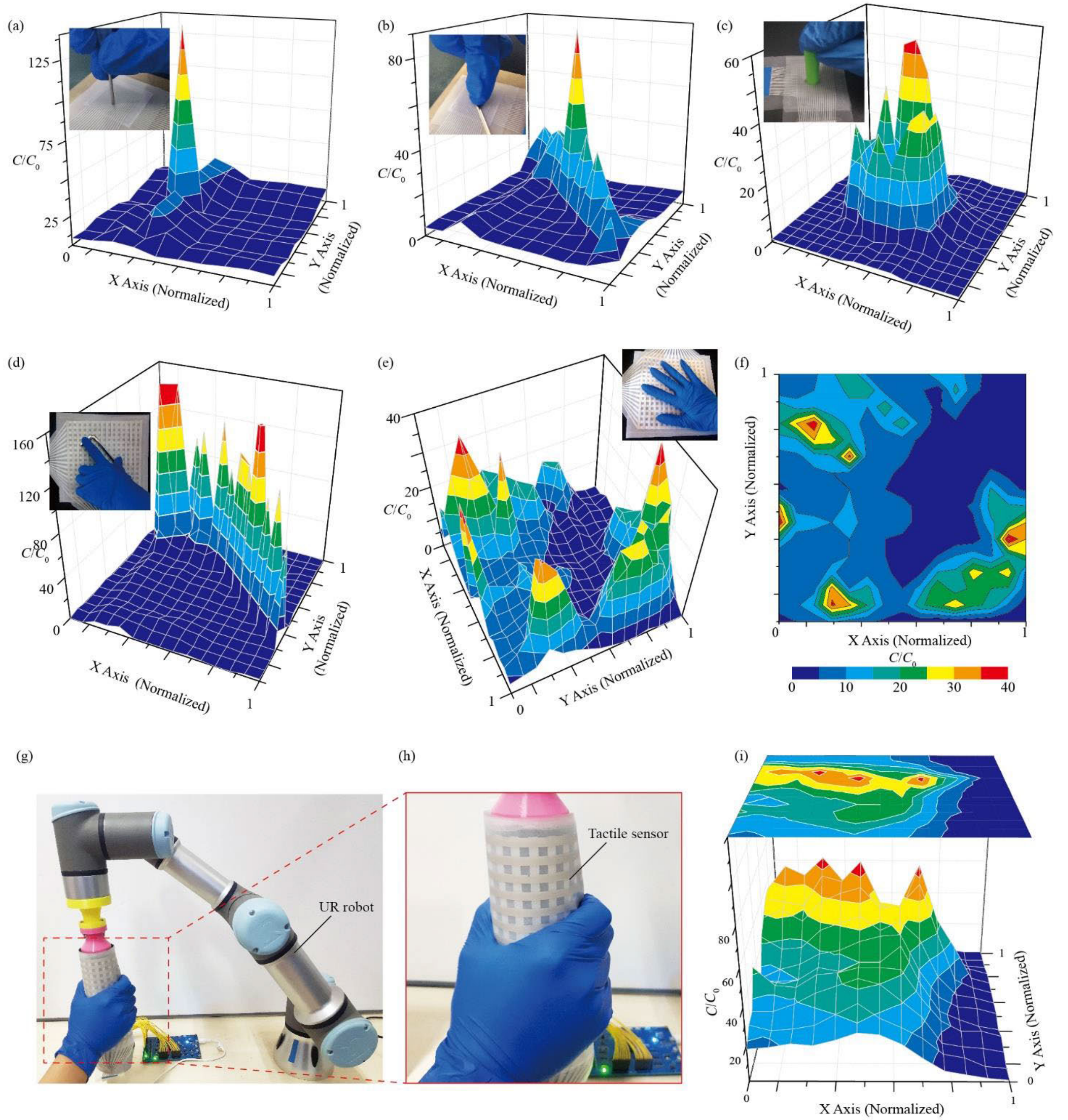

FIGURE 7. Pressure distribution tests with different tactile sensors. (a) to (c) Pressure array data under different pressure loads using tactile sensors with high spatial resolution (1 mm spacing between 1 mm-wide electrodes and 20 × 20 capacitive sensing units). (d) to (i) Pressure array data under different pressure loads using tactile sensors with large measurement area (5 mm spacing between 5 mm-wide electrodes and 20 × 20 sensing units). The measurement circuitry used in the test are demonstrated in the supplementary document.

tactile sensor mentioned in this study. The principle of the capacitance array measurement and the experimental results are illustrated in Fig. 7 (details in the supplementary document). The sensor array measurement circuit was optimized based on the reference [33], and it could scan 32 × 32 units at the frequency of 10 kHz during the pressure variation distribution mapping.

To further demonstrate the applicability and the universality of the work, tactile sensor with different spatial resolutions and measurement areas were fabricated and tested, as illustrated in Fig. 7. Fig. 7(a) to 7(c) are the experiment results of the tactile sensor with high spatial resolution (2 units/mm^2) under different pressure loads, such as force exerted in a single point, or in lines or in circles. The plotted data of

TABLE 1. Comparison between supercapacitive tactile sensors.

	Previous work	This work
Sensitivity	10 nF·kPa^{-1} [17] 114 nF·kPa^{-1} [16] 5.28 nF·kPa^{-1} [27] 108.2 nF·kPa^{-1}·cm^2 [26]	135.9 nF·kPa^{-1}·cm^2 (Upper limit, structure-dependent)
Measurement range	0–25 kPa [17] 7–18 kPa [27]	0–1200 kPa (Upper limit, structure-dependent)
Spatial resolution	>1 points/mm^2 [16, 26, 27]	Sub-mm, 2 points/mm^2
Measurement area	Not applicable	>400 mm × 400 mm (For a single sensor without splicing)

capacitance variation could well reflect the pressure load amplitude and spatial distribution. Fig. 7(d) to 7(i) demonstrate the pressure distribution mapping using tactile sensors with larger measureable area (2 units/100 mm^2) under different types of pressure loads. All the exerted pressure load was well observed using the developed sensing system, which validates the usefulness and the application versatility of the flexible tactile sensor. Especially, Fig. 7(i) illustrates the data from a field test when the larger-area tactile sensor was wrapped to the UR robot (UR3, Universal Robots, Denmark), and the hand-holding pressure was mapped using the developed sensing system. It infers that the flexible system would be fully functional and robust in the real human-robot interaction applications. There were also noises observed during the test, as plotted in the figure. Multiple factors would lead to interferences or pressure non-uniformity, such as manual factors during the force exertion, coupled capacitance between electrodes, the environmental interferences and so on. These could be solved by measurement circuit improvement and structural parameter optimization in further studies, but they have limited influence on the pressure distribution observation as demonstrated in the data.

V. CONCLUSION

A new type of flexible supercapacitive tactile sensor for human-robot interaction is introduced in this paper. It owns various advantages over the previously reported sensors, such as high spatial resolution, wide measurement range, low cost, simple fabrication, and linear characteristics, as shown in Table 1.

The sensor is built with simple structures, as two layers of flexible electrodes and a layer of ionic microfiber membrane, to form electrostatic double-layer capacitors (EDLCs) at the contact interfaces. The capacitance of the sensor unit varies during the elastic deformation when under external pressure loads. The fabrication of the flexible electrodes and the ionic-gel coated microfiber matrix is cost- and time-efficient following simple protocols, which enlarges the potential application areas. Characterizations with static pressure suggest robust linear relationships between the capacitance variation and the applied pressure load. By tuning the structural parameters such as the thickness of the ionic membranes, high pressure sensitivity (135.9 nF·kPa^{-1}·cm^2 or 27.11 kPa^{-1}) and wide pressure measurement range (from 0 kPa to 1200 kPa) are separately demonstrated. Dynamic pressure cycles from press machine and human finger tapping have been used to test the dynamic response. The tactile sensor could well reflect the pressure cycles based on the experimental data. Further, different types of tactile sensors have been used to measure the spatial pressure distribution under types of pressure load. It demonstrates the applicability of high spatial resolution and large measurement area of the tactile sensor that could satisfy the human-robot interaction applications. The developed flexible pressures sensor owns superior sensitivity, high spatial resolution, low cost, simple fabrication and linear characteristics, which enlarges the universal access to the robotic tactile sensing and indicates good candidacy for various application fields. Further studies, such as ultrahigh spatial resolution, sensing robustness, scalable fabrication and assembly, are in progress. Still, the optimization of the tradeoff relationships among the sensor sensitivity, maximum measurement range and sensing area is also a significant section of the future studies.

REFERENCES

[1] R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing—From humans to humanoids," *IEEE Trans. Robot.*, vol. 26, no. 1, pp. 1–20, Feb. 2010.

[2] T. Sekitani, H. Nakajima, H. Maeda, T. Fukushima, T. Aida, K. Hata, and T. Someya, "Stretchable active-matrix organic light-emitting diode display using printable elastic conductors," *Nature Mater.*, vol. 8, no. 6, pp. 494–499, Jun. 2009.

[3] Z. Fan, J. C. Ho, T. Takahashi, R. Yerushalmi, K. Takei, A. C. Ford, Y.-L. Chueh, and A. Javey, "Toward the development of printable nanowire electronics and sensors," *Adv. Mater.*, vol. 21, no. 37, pp. 3730–3743, Oct. 2009.

[4] W. Wu, X. Wen, and Z. L. Wang, "Taxel-addressable matrix of vertical-nanowire piezotronic transistors for active and adaptive tactile imaging," *Science*, vol. 340, no. 6135, pp. 952–957, May 2013.

[5] T. Mukai, S. Hirano, H. Nakashima, Y. Kato, Y. Sakaida, S. Guo, and S. Hosoe, "Development of a nursing-care assistant robot RIBA that can lift a human in its arms," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2010, pp. 5996–6001.

[6] M. L. Hammock, A. Chortos, B. C.-K. Tee, J. B.-H. Tok, and Z. Bao, "25th anniversary article: The evolution of electronic skin (E-Skin): A brief history, design considerations, and recent progress," *Adv. Mater.*, vol. 25, no. 42, pp. 5997–6038, Nov. 2013.

[7] S.-E. Zhu, M. Krishna Ghatkesar, C. Zhang, and G. C. A. M. Janssen, "Graphene based piezoresistive pressure sensor," *Appl. Phys. Lett.*, vol. 102, no. 16, Apr. 2013, Art. no. 161904.

[8] W. Choi, J. Lee, Y. K. Yoo, S. Kang, J. Kim, and J. H. Lee, "Enhanced sensitivity of piezoelectric pressure sensor with microstructured polydimethylsiloxane layer," *Appl. Phys. Lett.*, vol. 104, no. 12, Mar. 2014, Art. no. 123701.

[9] S. Yamada, T. Sato, and H. Toshiyoshi, "A pressure sensitive ionic gel FET for tactile sensing," *Appl. Phys. Lett.*, vol. 110, no. 25, Jun. 2017, Art. no. 253501.

[10] W. Gao, S. Emaminejad, H. Y. Y. Nyein, S. Challa, K. Chen, A. Peck, H. M. Fahad, H. Ota, H. Shiraki, D. Kiriya, D.-H. Lien, G. A. Brooks, R. W. Davis, and A. Javey, "Fully integrated wearable sensor arrays for multiplexed *in situ* perspiration analysis," *Nature*, vol. 529, no. 7587, pp. 509–514, Jan. 2016.

[11] D.-H. Kim, "Epidermal electronics," *Science*, vol. 333, no. 6044, pp. 838–843, Aug. 2011.
[12] A. Chortos, J. Liu, and Z. Bao, "Pursuing prosthetic electronic skin," *Nature Mater.*, vol. 15, no. 9, pp. 937–950, Sep. 2016.
[13] Y. Huang, X. Fan, S. Chen, and N. Zhao, "Emerging technologies of flexible pressure sensors: Materials, modeling, devices, and manufacturing," *Adv. Funct. Mater.*, vol. 29, no. 12, Mar. 2019, Art. no. 1808509.
[14] S. C. B. Mannsfeld, B. C.-K. Tee, R. M. Stoltenberg, C. V. H.-H. Chen, S. Barman, B. V. O. Muir, A. N. Sokolov, C. Reese, and Z. Bao, "Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers," *Nature Mater.*, vol. 9, no. 10, pp. 859–864, Oct. 2010.
[15] R. Li, Y. Si, Z. Zhu, Y. Guo, Y. Zhang, N. Pan, G. Sun, and T. Pan, "Supercapacitive iontronic nanofabric sensing," *Adv. Mater.*, vol. 29, no. 36, Sep. 2017, Art. no. 1700253.
[16] S. Li, N. Pan, Z. Zhu, R. Li, B. Li, J. Chu, G. Li, Y. Chang, and T. Pan, "All-in-One iontronic sensing paper," *Adv. Funct. Mater.*, vol. 29, no. 11, Mar. 2019, Art. no. 1807343.
[17] S. Wang, J. Xu, W. Wang, G.-J.-N. Wang, R. Rastak, F. Molina-Lopez, J. W. Chung, S. Niu, V. R. Feig, J. Lopez, T. Lei, S.-K. Kwon, Y. Kim, A. M. Foudeh, A. Ehrlich, A. Gasperini, Y. Yun, B. Murmann, J. B.-H. Tok, and Z. Bao, "Skin electronics from scalable fabrication of an intrinsically stretchable transistor array," *Nature*, vol. 555, no. 7694, pp. 83–88, Mar. 2018.
[18] S. Sundaram, P. Kellnhofer, Y. Li, J.-Y. Zhu, A. Torralba, and W. Matusik, "Learning the signatures of the human grasp using a scalable tactile glove," *Nature*, vol. 569, no. 7758, pp. 698–702, May 2019.
[19] W. Lee, D. Kim, J. Rivnay, N. Matsuhisa, T. Lonjaret, T. Yokota, H. Yawo, M. Sekino, G. G. Malliaras, and T. Someya, "Integration of organic electrochemical and field-effect transistors for ultraflexible, high temporal resolution electrophysiology arrays," *Adv. Mater.*, vol. 28, no. 44, pp. 9722–9728, Nov. 2016.
[20] S. Lee, A. Reuveny, J. Reeder, S. Lee, H. Jin, Q. Liu, T. Yokota, T. Sekitani, T. Isoyama, Y. Abe, Z. Suo, and T. Someya, "A transparent bending-insensitive pressure sensor," *Nature Nanotechnol.*, vol. 11, no. 5, pp. 472–478, May 2016.
[21] B. C.-K. Tee, A. Chortos, R. R. Dunn, G. Schwartz, E. Eason, and Z. Bao, "Tunable flexible pressure sensors using microstructured elastomer geometries for intuitive electronics," *Adv. Funct. Mater.*, vol. 24, no. 34, pp. 5427–5434, Sep. 2014.
[22] J. Liu, N. Liu, K. Hashimoto, C. Meng, and S. Guo, "Touch position identification based on a flexible array-less supercapacitive tactile sensor," *AIP Adv.*, vol. 9, no. 1, Jan. 2019, Art. no. 015026.
[23] B. Nie, S. Xing, J. D. Brandt, and T. Pan, "Droplet-based interfacial capacitive sensing," *Lab Chip*, vol. 12, no. 6, pp. 1110–1118, 2012.
[24] B. Nie, R. Li, J. Cao, J. D. Brandt, and T. Pan, "Flexible transparent iontronic film for interfacial capacitive pressure sensing," *Adv. Mater.*, vol. 27, no. 39, pp. 6055–6062, Oct. 2015.
[25] X. Yang, Y. Wang, H. Sun, and X. Qing, "A flexible ionic liquid-polyurethane sponge capacitive pressure sensor," *Sens. Actuators A, Phys.*, vol. 285, pp. 67–72, Jan. 2019.
[26] X. Yang, Y. Wang, and X. Qing, "A flexible capacitive pressure sensor based on ionic liquid," *Sensors*, vol. 18, no. 7, p. 2395, 2018.
[27] N. Matsuhisa, D. Inoue, P. Zalar, H. Jin, Y. Matsuba, A. Itoh, T. Yokota, D. Hashizume, and T. Someya, "Printable elastic conductors by *in situ* formation of silver nanoparticles from silver flakes," *Nature Mater.*, vol. 16, no. 8, pp. 834–840, Aug. 2017.
[28] T. Q. Trung and N.-E. Lee, "Flexible and stretchable physical sensor integrated platforms for wearable human-activity monitoringand personal healthcare," *Adv. Mater.*, vol. 28, no. 22, pp. 4338–4372, Jun. 2016.
[29] W. J. Hyun, E. B. Secor, M. C. Hersam, C. D. Frisbie, and L. F. Francis, "High-resolution patterning of graphene by screen printing with a silicon stencil for highly flexible printed electronics," *Adv. Mater.*, vol. 27, no. 1, pp. 109–115, Jan. 2015.
[30] S. Khan, L. Lorenzelli, and R. S. Dahiya, "Technologies for printing sensors and electronics over large flexible substrates: A review," *IEEE Sensors J.*, vol. 15, no. 6, pp. 3164–3185, Jun. 2015.
[31] S. Kumar, G. Liu, D. W. Schloerb, and M. A. Srinivasan, "Viscoelastic characterization of the primate finger pad *in vivo* by microstep indentation and three-dimensional finite element models for tactile sensation studies," *J. Biomech. Eng.*, vol. 137, no. 6, Jun. 2015, Art. no. 061002.
[32] V. Maheshwari and R. Saraf, "Tactile devices to sense touch on a par with a human finger," *Angew. Chem. Int. Ed.*, vol. 47, no. 41, pp. 7808–7826, Sep. 2008.
[33] S. Guo, T. Shiraoka, S. Inada, and T. Mukai, "A two-ply polymer-based flexible tactile sensor sheet using electric capacitance," *Sensors*, vol. 14, no. 2, pp. 2225–2238, 2014.

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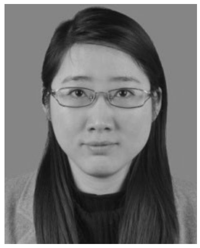

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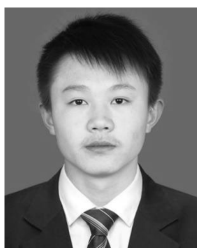

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