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Development of a flexible PDMS capacitive pressure sensor for plantar pressure measurement

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ABSTRACT

A flexible capacitive pressure sensor has been developed for plantar pressure measurement in biomechanical application. Polydimethylsiloxane (PDMS) material was selected as the material of the dielectric layer because of its advantages of high dielectric constant and tunable elasticity. In this work, PDMS characterization was conducted to investigate the stiffness under different mixing ratios of PDMS pre-polymer and the curing agent. PDMS in 16:1 mixing ratio was selected since it has the most linear stress–strain relationship with the highest elasticity within our pressure region of interest. Since the sensor was designed for the measurement of the plantar pressure, it can measure the pressure up to 945 kPa. Moreover, flexible printed circuit film was utilized as the sensor substrate for the minimum disturbance of the measurement to the curved surface and reservation of the electronic circuit integration. Because of the miniaturization and flexibility of the sensor, it has the potential to develop shoe-integrated sensor system for long-distance data collection for gait analysis.

1. Introduction

In rehabilitation science, assessment of patients associated with knee steoarthritis and stoke can be carried out by gait analysis, which is the investigation of walking [1,2]. This can be conducted by the tracking system in motion laboratory [3], clinician visual observation, or pressure sensing [4–7]. The first method is expensive, requires the maintenance of a dedicated system, and uses cumbersome equipment attached to the patient, but produces well-quantified and accurate results. The second method is qualitative, unreliable, and difficult to compare across multiple visits. The third method can be performed using a mat embedded with pressure sensors [4,5] and shoe-integrated sensor system [6,7]. This is capable of measuring quantitative and repeatable results. Moreover, the shoe-integrated sensor system can provide gait analysis outside laboratory for long-distance study. The system can directly measure the plantar pressure distribution based on the force-sensitive resistors (FSRs) integrated into the shoe. This provides clinicians and patients new opportunities for diagnosis and treatment of chronic walking problems.

Most of the pressure sensors available in the market lack the flexibility to fit into a curved interface. Since plantar pressure measurement is performed between the foot and shoe while walking, flexibility of sensors could improve the measurement accuracy and sensor durability. Using micro-fabrication technology, pressure sensors based on resistive and capacitive sensing mechanisms were reported in the literature. In the former group, resistive-metal-based sensing elements were utilized as the sensing materials [8]. A flexible microsensor array was fabricated by microfabrication techniques. This flexible sensor was composed of many silicon islands that were interconnected by two layers of polyimide film. Another research group reported a miniaturized and flexible optoelectronic sensing system [9]. Three MEMS pressure sensors were integrated into flexible substrates for tactile skin applications. Moreover, a flexible pressure sensor with the piezoresistive cantilever standing vertically on polydimethylsiloxane (PDMS) substrate has been developed [10]. Also, a flexible tactile sensor for both normal and shear load detection was reported [11]. Four metal strain gauges were integrated into the polymer substrate. The resistive-metal-based sensor can provide good sensitivity. However, complicated micro-fabrication processes were involved in the above microsensors, especially for the array sensing. For the capacitive mechanism, a 3-axis capacitive tactile sensor was reported in [12]. It consisted of four capacitors embedded in a rubber substrate and gave good performance for the applications requiring large covering areas. Moreover, pressure sensors employing optical fibers as the building blocks of sensing elements have been developed [13–15]. However, bulky and expensive equipment are required for the operation of these optical pressure

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sensors. Furthermore, a capacitive sensing element embedded in the PDMS micro-machined structure was developed for the artificial skin in robotic applications [16]. This pressure sensor was designed to sense small forces on the surface. However, few studies have been reported on flexible microsensors for the large pressure measurement in biomechanical applications.

In this work, a flexible capacitive microsensor constructed by tunable PDMS layer is described for plantar pressure measurement and suitable for many biomechanical applications. The sensor consists of 4 layers including lower layer, dielectric layer, upper layer, and bump layer. The lower layer and upper layer are flexible printed circuit film and the dielectric layer and bump layer are made by PDMS material. PDMS is an elastomer and has high dielectric constant and tunable elasticity, which can be adjusted by different mixing ratios of the PDMS pre-polymer and the curing agent during formation. We adopt the advantages of the PDMS to design the pressure sensor. However, it has high nonlinear stress–strain relationship. In order to compensate the disadvantages, investigation of the PDMS stress–strain characteristics was conducted to select suitable mixing ratio for the dielectric layer of the sensor. Also, four sensing electrodes were fabricated on the lower layer to generate four independent capacitive signals for accurate measurement. From our results, the sensor can measure pressure up to 945 kPa and is suitable for the plantar pressure measurement in many biomechanical applications, such as monitoring of diabetic foot and ergonomic studies on foot wears.

2. Design and fabrication of the PDMS capacitive microsensor

The capacitive pressure sensor consisted of four layers: a lower layer, a dielectric layer, an upper layer, and a bump layer, as illustrated in Fig. 1. The lower layer and upper layer were flexible printed circuit film to provide a flexible substrate and be compatible to the peripheral electronic circuit for future development. The dielectric layer was made of PDMS material and the electrodes were located on its top and bottom surfaces. Four electrodes on the lower layer and one common electrode on the upper layer were fabricated to provide four independent capacitance measurements. The bump layer provided a point contact between the applied force and the sensor for even pressure distribution. The working principle of the sensor is to measure the capacitance change to estimate the applied pressure. When there is no pressure applied to the sensor, the capacitances are recorded as zero. When a pressure is applied, the distance of the dielectric layer is reduced. The capacitance values among four independent measurements increases. Since the deformation of the dielectric layer may not be uniform, four independent measurements could improve the accuracy of the pressure estimation.

The fabrication process of the sensor is illustrated in Fig. 2. The copper coated polyimide film was purchased from Taiflex Scientific Co. Ltd., Taiwan and the PDMS material was Sylgard® 184 from Dow Corning, USA. Since the polyimide film is flexible and cannot be used in standard microfabrication process, it was fixed on a glass substrate by spin-coated PDMS. The PDMS was prepared by thoroughly mixing the PDMS pre-polymer and curing agent in a certain weight ratio. The PDMS mixture was ready by degassing under a vacuum chamber. Hence, the electrodes on the polyimide film were fabricated by photolithography with the pattern of upper and lower electrodes in the diameter of 6 mm. A 30 μm thick dielectric PDMS layer was spin-coated on the lower layer by controlling the spinning speed. A thin layer of PDMS was spin-coated on the upper layer for the adhesion among upper and lower layer. A PMDS spherical bump layer was molded using a polymethyl methacrylate (PMMA) mold fabricated by micro-machining equipment. The diameter and height of the bump were 6 and 3 mm, respectively. The sensor was assembled by bonding each layer by surface plasma treatment. In the PDMS process, the standard mixing ratio of PDMS pre-polymer and curing agent is 10:1 according to the manufacturer's instruction. However, different elasticity can be achieved by different mixing ratios. In this case, the mixing ratios were different for different layers based on their purpose. Because the dielectric layer was a compressive layer in the pressure measurement, flexibility can improve the sensitivity of the sensor. The mixing ratio of 16:1 was selected for the dielectric layer and will be described in the next section. Moreover, since the bump layer was designed as the contact point for the applied force, rigidity was desired for even pressure distribution on the sensor. The mixing ratio of 4:1 was selected to fabricate the bump layer.

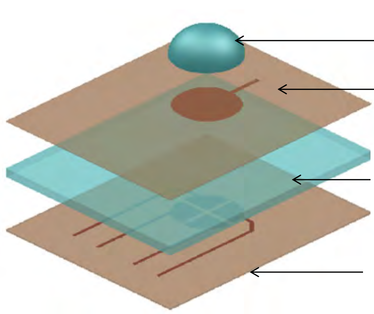

Fig. 1. Illustration of the structure of the capacitance microsensor.

3. Characterization of PDMS

The dielectric constant and elasticity of the dielectric layer can influence the sensitivity of the sensor. They determine the electrical and mechanical properties of the microsensor respectively. Because PDMS has the advantages of high dielectric constant and tunable elasticity, it was selected as the material of the dielectric layer of the sensor for this particular application. The elasticity of the PDMS can be tuned by the adjustment of the mixing ratio of the PDMS pre-polymer and curing agent. Investigation of the characteristics of PDMS in different mixing ratios was performed to understand the stress–strain relationship for the optimal design of the sensor.

Material testing was conducted to characterize the stiffness of the PDMS material under 5 mixing ratios of the PDMS pre-polymer and the curing agent, i.e., 12:1, 16:1, 20:1, 24:1, and 28:1. The tunable elasticity could benefit the sensitivity and adjust the range of force sensing. The characterization procedure of PDMS is described briefly. The mixture of PDMS pre-polymer and curing agent was degassed under a vacuum chamber and then poured into the pre-fabricated cylindrical mold (12 mm in diameter and 13 mm in height). Then, it was baked at 70 °C for around 2 h. In this way, the cylindrical PDMS specimens under five mixing ratios were fabricated respectively. The stiffness of the specimens was measured by materials testing equipment (Model: 5544, Instron Inc.). Displacement control was conducted to measure the relationship between the pressure and the *z*-axis displacement of the PDMS specimens. The sampling frequency was 5 Hz and the measurement was repeated three times for each specimen. During the measurement, the specimens were in elastic region, i.e., reversible deformation. The stiffness of the PDMS varied under different mixing ratios. The stress and strain (σ–ε) curves of the specimens were plotted in Fig. 3. The elasticity increased by increasing the portion of the PDMS pre-polymer. Moreover, the stress–strain relationship became nonlinear for PDMS specimens with high portion of PDMS pre-polymer.

The capacitive sensor was designed for the measurement of large pressure range. For the diabetic patients, the pressure between the foot and walking surface is up to 400 kPa [17]. Therefore,

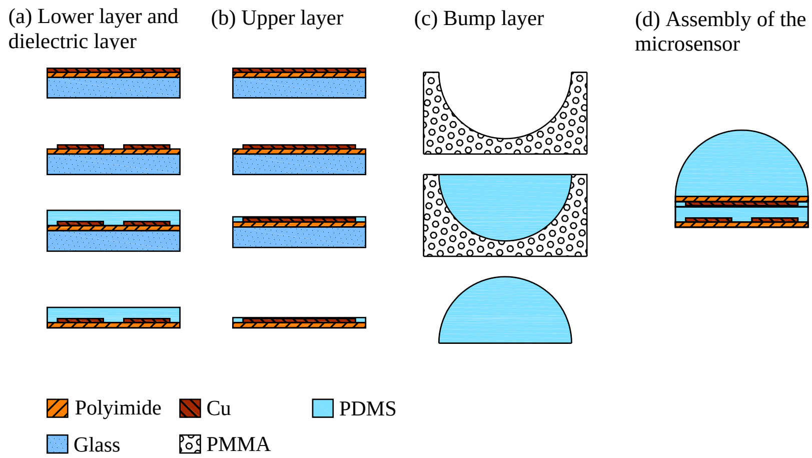

Fig. 2. Fabrication process of the capacitive microsensor. (a) Fabrication of the lower substrate and the dielectric layer. (b) Fabrication of the upper substrate. (c) Fabrication of the bump layer. (d) Assembly of the microsensor.

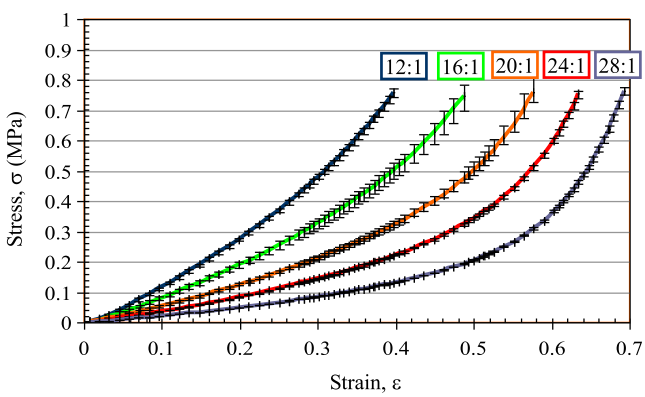

Fig. 3. The stress and strain curves of the PDMS specimens with different mixing ratios of PDMS pre-polymer and curing agent (12:1, 16:1, 20:1, 24:1, and 28:1).

selection of the PDMS mixing ratio was based on the above pressure. The selection criterion was the stress–strain curve that showed the higher linearity with the highest elasticity. This consideration could enhance the linearity and sensitivity of the sensor. Good linearity can reduce the complexity of interpretation of the stresses and high elasticity can increase the change of capacitance values for higher sensitivity. Since the interested region of the pressure is below 400 kPa, the PDMS dielectric layer formed by 16:1 mixing ratio of the PDMS pre-polymer and curing agent has selected based on the above criterion.

4. Experimental results

The fabricated sensor was tested under a moving stage with a force gauge (Model: JSV-H1000 and HF-10, Japan Instrumentation System). The force gauge was attached on the *z*-axis of the moving stage. The capacitance values of the sensor were measured by a capacitance meter (Model: 9216A, Protek). The sensor was attached on the moving stage and aligned with the precision *x*–*y* table mounted on the stage, as shown in Fig. 4. The measurement was conducted by the downward movement of the *z*-axis of the moving stage. While the force gauge contacted the bump of the sensor, the bump was pushed and the dielectric layer of the sensor was compressed. The bump provides a contact point to the force gauge and generates even pressure distribution to the dielectric layer. The relationship of the applied force and capacitance values can be measured by the force gauge and the capacitance meter,

Fig. 4. Photo of the experimental setup. The pressure sensor was mounted on the moving stage. The relationship of applied force and capacitance values was measured by the force gauge and capacitance meter, respectively.

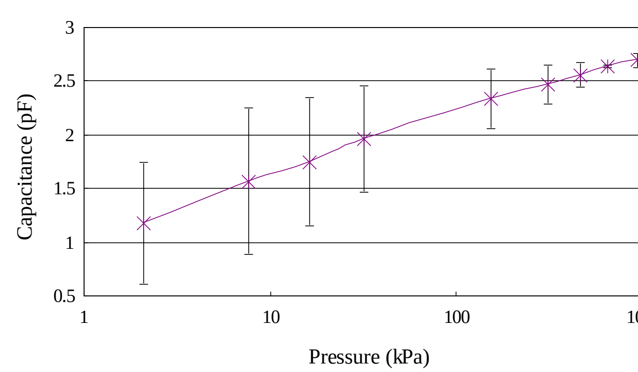

Fig. 5. The capacitance change of the sensor under pressure. Four capacitance values of the sensor were averaged for accurate measurement.

respectively. The pressure was calculated by the applied force under the sensor area, i.e., $A = \pi r^2$. The measurement result is shown

Table 1
Comparison of different pressure sensors.

Operation principle	Our sensor	Lee et al. [18]	Kim et al. [19]	Hasegawa et al. [20]	Li et al. [21]	Chuang et al. [22]	Li et al. [23]
	Capacitive				Piezoelectric		
Sensitivity	6.8%/N	3%/mN	4%/mN	–	10.6 mV/N (maximum)	6.2 mV/N	–
Range	0–945 kPa	0–250 kPa	0–0.3 N	0–350 mN	0–40 mN	0.5–4 N	0–1.2 Bar
Initial value	0.95 pF	0.18 pF	0.90 pF	0.70 pF	–	–	–
Dielectric/ piezoelectric materials	PDMS	Air	Air	Elastic tube and air	PVDF-TrFE copolymer	PVDF	Ni-PDMS
Application	Plantar pressure measurement	Artificial skin for robot	Touch screen	Body contact pressure measurement	Invasive surgical devices	Physiology monitoring systems	Microfluidic systems

in Fig. 5. Large standard deviation (0.46–0.67) among four sensing elements was measured in the applied pressure below 100 kPa. It was suspected because of the limitation of fabricating a true even thickness dielectric layer by spin-coating. The thickness variation may induce the inaccurate measurement especially occurring in the measurement of small pressure. In this work, in order to eliminate the effect of the thickness variation, the sensing area was divided into four sections for four independent sensing elements. The thickness variation in each sensing element could be reduced. Therefore, the total capacitance of the sensor averaged the capacitances produced by the four sensing elements. The pressure can be measured up to 945 kPa and the capacitance value was from 0.95 to 2.69 pF.

5. Discussions

A number of pressure sensors have been reported in the literature. A comparison table of capacitive and piezoelectric pressure sensors is listed in Table 1. Since our sensor is designed for the plantar pressure measurement, the applied force is in both static and dynamic format and the measurement range should be up to 400 kPa [17]. Therefore, considering to the piezoelectric operation, the piezoelectric voltage is generated from the oscillating pressure. Although they have good sensitivity, but the measurement can only apply to dynamic format and the range is small. The piezoelectric operation may not be suitable for plantar pressure measurement. Alternatively, most of the capacitive pressure sensors were developed for small force sensing. The dielectric layer was mainly composed of air that can have the largest compressed distance to enhance the sensitivity. However, the dielectric constant of air is 1 that makes the initial capacitance relatively small. The measurement should be isolated to avoid coupling capacitance from environment. Also, the measurement range was limited and these capacitive sensors were suitable for the touch sensing applications. In order to develop the pressure sensor for plantar pressure measurement, we selected PDMS material for the dielectric layer that has several advantages. The dielectric constant of the PDMS material is 2.65. Compared with same dimension of two parallel electrode plates, PDMS material can generate higher capacitance than air. Also, the elasticity of PDMS material can be tuned by the mixing ratio of PDMS pre-polymer and curing agent during the formation process. The measurement range can be adjusted based on the particular application. Moreover, because the PDMS is a solid material, the sensor is simply composed of three layers, i.e., upper electrode layer, PDMS dielectric layer, and lower electrode layer, to avoid the hollow structure in other capacitive sensors. The fabrication process becomes simple and enhances the yield rate. Moreover, integration of the FSRs into the shoe is an important tool to detect gait while ambulatory walking. However, using the commercial available FSRs for the integration is a challenge while the sensing nodes are dense [6,7]. In our current study, flexible printed circuit film was utilized for the sensor substrate. It is not only providing a flexible substrate for fitting into a curved interface, but also the peripheral electronic circuit can be fabricated on the same substrate for future integration. Therefore, a printed circuit film can integrate the pressure sensors with the signal amplifiers, filters, and wireless system.

6. Conclusions

A flexible capacitive sensor is developed for the measurement of plantar pressure in biomechanical application. The sensor consisted of four layers: lower layer, dielectric layer, upper layer, and bump layer. The change of capacitance values can directly represent the applied pressure. Since PDMS has the advantages of high dielectric constant and tunable elasticity, it was selected as the material of the dielectric layer for the sensor. However, PDMS is an elastic material that has high nonlinear stress–strain relationship. The characterization of PDMS was conducted to found out the stiffness under different mixing ratios of the PDMS pre-polymer and the curing agent. PDMS in 16:1 mixing ratio was selected since it has the most linear stress–strain relationship with the highest elasticity within our pressure region of interest. The sensor can measure the pressure up to 945 kPa and is capable for most of the plantar pressure measurement. Moreover, flexible printed circuit film was utilized as the sensor substrate for the minimum disturbance of the measurement to the curved surface and reservation of the electronic circuit integration. Because the sensor is miniaturized and flexible, it has the potential to be integrated into the shoe for long-distance data collection for gait analysis.

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