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Instrumented rubber insole for plantar pressure sensing

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ABSTRACT

We demonstrate a printed pressure sensor embedded rubber insole for measurement and analysis of plantar pressure. Unlike the conventional mode of pressure sensing of interdigitated capacitors in which change in dimension of electrodes by external pressure leads to variation of capacitance, for this study, the change in capacitance is entirely led by variation of relative permittivity of the surrounding dielectric medium with applied pressure. The measured sensitivity of the sensor is 4.3 V/MPa and shows high linearity in the pressure exerted by human weight. The plantar pressure is detected with locally embedded sensors to register various foot postures at three high-pressure regions: hind-foot, mid-foot, and fore-foot.

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1. Introduction

Measurement and analysis of plantar pressure caused by contact between human body and external environment is of importance because this pressure directly affects human body. Foot is an organ which stands the biggest pressure for the longest time among human body parts, and thus plantar pressure monitoring is vital for human healthcare applications. Accordingly, analysis of plantar pressure has been used for many applications including footwear design [1,2], performance improvement and injury prevention of sports players [3], clinical gait analysis [4,5] and diagnosis of foot-related diseases [6] such as diabetic ulceration, plantar fasciitis and arthritis. Tactile pressure sensors have been intensively researched to imitate human skin and to measure tactile pressure which ranges from several pascal (Pa) to several kPa [7,8]. Although this tactile pressure sensor can give good sensitivity, measurable pressure range is too narrow and small for plantar pressure which can reach several MPa [9]. Thus, pressure sensors which operate at high pressure are required for plantar pressure.

The in-shoe type plantar pressure measurement system can provide real-life value of plantar pressure by measuring the pressure as installed inside the shoes [10]. Piezoresistive pressure sensors have been reported for in-shoe type sensors [11]. However, this piezoresistive pressure sensor shows lower sensitivity and much higher temperature dependence than capacitive ones. Thus, the piezoresistive sensor is difficult to ensure reliable data under physically rigorous environment such as an insole. Temperature inside shoes can fluctuate by about 6 °C during movement [12]. Among capacitive pressure sensors, the interdigitated capacitor (IDC) is a unique candidate as a pressure sensor due to their miniature size, light weight, reduced parasitic capacitance and very good sensitivities [13]. An external physical force causes dimensional changes of the overlapping length on interdigitated electrodes (IDEs), which in turn causes a change in capacitance. But an alternative theory has also been investigated by some researchers where any buffer medium can also act as a pressure transmitter, that is, the medium surrounding the electrodes is compressed which alters the relative permittivity of the medium [14]. A flexible polymer like polydimethylsiloxane (PDMS) is a suitable buffer medium for pressure sensing on insoles. A capacitive pressure sensor with PDMS with two copper electrodes has been reported [15]. In this sensor, distance between two laminating electrodes changes and leads to capacitance change. The in-shoes sensor is exposed to repeated real-life movements, so the movement of the sensor itself can cause damage and lead to failure of measurement. Thus, capacitance change with little dimensional change of capacitors can help this situation. And small initial capacitance of the previous capacitive pressure sensor could be also a negative factor against reliability of measured data because parasitic capacitance which may be a few pF from the environment can adversely affect the data [16]. IDCs can have much higher initial capacitance because of large overlapping area in the same area and thus, more reliable data can be obtained.

Mechanical reliability for maintaining sensor's performance is another important requirement for the insole applications because repeated compressive, stretching and shear stresses are applied on the shoe insole during movement. Deposited metal thin film is known to be easily broken when the substrate is mechanically deformed because of poor attachment to the substrate [17].

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Among various metal patterning methods, the direct stamping method of silver nanoparticles (AgNPs) is simple to apply ensuring good attachment of metal thin film to the substrate with a UV-curable adhesive which also tightly holds AgNPs by conformal contact to substrate [18,19]. The AgNPs-based electrode has a high percolation threshold due to their spherical shapes [17]. Therefore, AgNP's tight holding is important to guarantee good conductivity as well as mechanical durability. Thus, the insole plantar pressure sensor which is continuously exposed to mechanically harsh environment is fabricated by the direct stamping method.

In this report, we fabricate an insole plantar pressure sensor by embedding printed IDCs into an elastic rubber, PDMS, and detect the sensor plantar pressure at different foot locations. The direct stamping method of AgNPs [18] is utilized in transferring the IDC pattern onto a flexible polyethylene terephthalate (PET) substrate, due to its ample advantages like mechanical durability, ease of fabrication, and efficient transfer of AgNPs. And the IDCs are then placed vertically in the foot sole mold which is three-dimensionally (3D) printed. PDMS is used as a dielectric medium for the IDCs as well as an encapsulating material which protects the embedded sensors. The entire assembly is interfaced with a capacitive interface circuit to measure pressure-to-voltage relation as well as capacitance variation with applied pressure. Dimensions of the prepared IDC are 10.2 mm for the length of each finger electrode, 100 μm for the width of each finger electrode, 16 μm for the gap between two consecutive electrodes, and 20 μm for the thickness of the electrodes. There are 200 finger electrodes in about 23 mm for guaranteeing high sensitivity. The printed IDC sensor is shown in Fig. 1(a) with an enlarged image showing IDEs.

2. Results and discussion

2.1. Design and fabrication of plantar pressure sensing insole

A 3D design of a human insole mold is created using well-known CAD software, SolidWorks, and is printed using a 3D printer. Three regions beneath foot, where the exertion of pressure is high, are chosen to be our locations of pressure sensors include the forefoot, the midfoot and the hindfoot, where an average human while standing can exert a maximum pressure of up to 1.9 MPa [10]. The three stamped IDCs (Fig. 1(a)) are vertically inserted into the insole mold as illustrated in Fig. 1(b); the face of the IDC looks to the left in the figure.

Table 1
Measured capacitance of an IDC before and after being embedded in PDMS.

Capacitance location	Initial capacitance (pF)	
	In air	In PDMS
Forefoot	69.3	70.5
Midfoot	66.8	67.2
Hindfoot	65.8	67.8

A simple capacitance-to-voltage converter circuit is designed and connected to the insole sensing system via a commercial DAQ system for voltage measurements with the aid of a simple LabVIEW program. The final instrumented insole system embedded with IDCs, capacitance-to-voltage converters and the DAQ kit is shown in Fig. 1(c). Before any actual measurement, initial capacitances are registered for all three sensors and are compared with the ones that are measured before PDMS encapsulation as tabulated in Table 1.

The increase in capacitance after PDMS encapsulation is due to the increase of the relative permittivity according to Eq. (1), when the surrounding air is replaced with PDMS.

$$C = \varepsilon_r \varepsilon_0 \frac{A}{a} \quad (1)$$

where C is capacitance, ε_r relative permittivity, ε_0 vacuum permittivity, A overlapping area of electrodes and a distance between two overlapping electrodes.

In Eq. (1), substrate's relative permittivity governs capacitance of the IDC when there is no surrounding dielectric material in the area of IDE's overlapped part except air. Thin IDCs, covered with dielectric materials have been reported that the dielectric

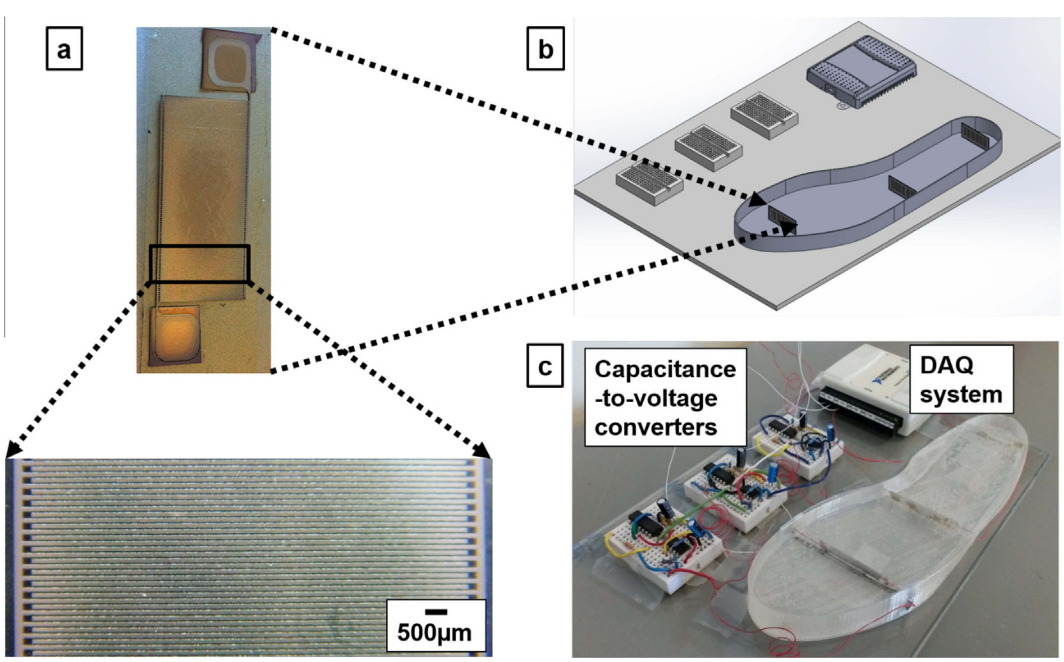

Fig. 1. (a) Fabricated IDEs stamped onto PET substrate, (inset) Optical Microscope image of the IDE pattern of one corner. (b) A SolidWorks assembly comprised of circuit boards, Data Acquisition Unit and the insole assembly with vertically placed pressure sensors. (c) Insole mold filled with cured PDMS and the interfacing circuits to convert measured capacitance into voltage.

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