Testing and comparing of film-type sensor materials in measurement of plantar pressure distribution

Satu Rajala, Timo Salpavaara, and Sampo Tuukkanen

***Abstract*—Simple in-shoe sensors based on film-type sensor materials were developed in this study. Three sensor materials were tested: polyvinylidenefluoride (PVDF), cellulose nanofibrils (CNF) and ElectroMechanical Film (EMFi). Plantar pressure distributions of a subject were measured with the developed in-shoe sensors; each consisting of three sensor channels (lateral and medial metatarsal heads and heel). In addition, piezoelectric sensor sensitivities and crosstalk between the sensor channels were determined. Differences between the tested film-type materials and measured plantar pressure distribution signals were studied.**

I. INTRODUCTION

Measurement of plantar forces has indicated a relationship between the excessive mechanical stress and ulceration of the foot [1]. The pressure ulcers occur when tissue is compressed under pressure, for instance, due to the use of improper footwear. At particular risk are heavily loaded regions overlying bony prominences, such as under the metatarsal heads, where the majority of plantar neuropathic ulcers occur [2]. The pressure ulcers are expensive and difficult to treat and even amputation may be required. An early identification of individuals at risk of ulceration is one of the primary means to reduce the incidence of ulceration [3].

During the last few decades, a variety of methods have been developed for the measurement of plantar stresses. For example, Shu *et al*. developed an in-shoe plantar pressure measurement and analysis system based on a textile fabric sensor array [4]. Perry *et al*. recorded the forefoot shear stress and pressure during the initiation of a gait with 16 transducers based on strain gauge technology [3]. Salpavaara *et al*. developed a laminated capacitive sensor matrix for plantar force measurements during sport events [5]. Lord and Hosein measured the in-shoe plantar shear stress locally beneath the metatarsal heads and heel with a sensor based on a magneto-resistor [2]. Piezoelectric and ferroelectret materials have been used by Razian and Pepper [6], Kärki *et al*. [7] and Hannula *et al*. [8]. Some devices for the plantar pressure measurements are also available commercially; however, they vary greatly in the cost and performance. For more information, some comprehensive review articles about the plantar pressure distribution measurements and sensors are available [1, 9-14].

In this study, we have developed the prototypes of simple in-shoe sensors based on film-type sensor materials. Three sensor materials are tested and compared: polyvinylidenefluoride (PVDF), cellulose nanofibrils (CNF) and ElectroMechanical Film (EMFi). All materials generate a charge when they are mechanically deformed, and thus, in principle, operated similarly. The sensors are fabricated on an insole electrode sheet and the obtained in-shoe sensor is placed inside a shoe for the plantar pressure distribution measurements. The results obtained with the in-shoe sensors in test measurements are reported and differences between the sensor materials are compared.

II. FILM-TYPE SENSOR MATERIALS

A. *Polyvinylidenefluoride (PVDF)*

PVDF is a piezoelectric viscoelastic material that generates a charge when it is mechanically deformed. During the manufacturing process, the polymer is stretched uniaxially and exposed to a high electric field to generate the piezoelectric properties [15]. PVDF is anisotropic material and thus its electrical and mechanical properties differ depending on the direction of an external force [15]. The electric flux density D of a PVDF sensor is defined in Eq. 1 as

$$D = \frac{Q}{A} = d_{ij}X_j \qquad (1)$$

where Q is the charge, A is the electrode area, d_{ij} is the piezoelectric coefficient for the axis of applied stress and X_j is the applied stress. The piezoelectric coefficient d_{ij} is related to the electric field produced by the mechanical stress [15]. The d_{ij} is a third-rank tensor conventionally expressed in terms of 3 x 6 matrix [16] as shown in Eq. 2.

$$d_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{pmatrix}. \qquad (2)$$

A polarized PVDF film has the d_{33} coefficient of -33 pC/N [15]. The PVDF material used here was purchased from Measurement Specialties Inc. (Hampton, USA). The thickness of the film was 28 µm.

B. *Cellulose nanofibrils (CNF)*

Cellulosic nanofibrils and nanocrystals [17], also called as nanocelluloses, are interesting renewable bio-based nanomaterials. Even though the piezoelectricity of wood has been known for decades [18], the topic has been covered in the scientific literature to a very limited extent and only a few recent studies report the experimental evidence of cellulose nanocrystals (CNC) piezoelectricity [19-21]. A polymer-like CNF films are composed of amorphous cellulose chains as well as crystalline CNC regions.

S. Rajala (née Kärki) is with the Department of Automation Science and Engineering, Tampere University of Technology, P.O. Box 692, FI-33101 Tampere, Finland (corresponding author to provide phone: +358 40 849 0941; e-mail: satu.rajala@tut.fi).

T. Salpavaara and S. Tuukkanen are with the Department of Automation Science and Engineering, Tampere University of Technology, P.O. Box 692, FI-33101 Tampere, Finland (e-mail: timo.salpavaara@tut.fi, sampo.tuukkanen@tut.fi).

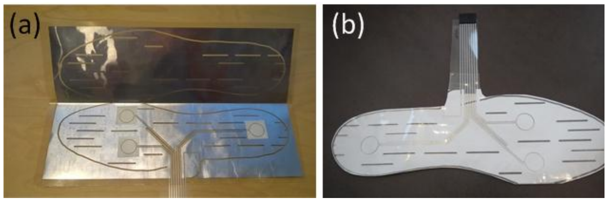

Figure 2. a) The in-shoe sensor construction and b) an example of the developed in-shoe sensor.

The CNF film used in this study was manufactured by a collaborator (the group of Prof. Orlando Rojas, School of Chemical Technology, Aalto University, Espoo, Finland). The CNF material was produced by a mechanical homogenizing process [22]. The process resulted in a bleached birch cellulose mass, which was then used for CNF film fabrication. Films were prepared by pressure filtering (15-30 min) followed by pressing and drying in hot-press at 100 °C for 2 h. The resulting in-house fabricated CNF films were about 70 µm thick. The piezoelectric sensitivity of 5-7 pC/N in the normal force direction has been previously reported for the CNF sensors [23].

A. ElectroMechanical Film (EMFi)

EMFi is a thin and elastic electroactive ferroelectret polymer film having a special cellular structure. The internal cellular structure is made by stretching the polyolefin material in a continuous biaxial orientation process that stretches the film in both in longitudinal and transversal directions [24]. Further the film is expanded at high-pressure gas-diffusion-expansion process [24]. The EMFi material is sensitive to force exerted normal to its surface, and the sensitivity of 250-400 pC/N has been reported for the film [24, 25]. The material consists of three layers: smooth and homogenous surface layers and a dominant, thicker midsection full of flat air-filled voids separated by polyolefin layers [24, 25].

The EMFi material is commercially available through a Finnish company Emfit Ltd. (Vaajakoski, Finland). The EMFi material used here was 80 µm thick.

III. MEASUREMENT SYSTEM

The insole electrode sheets for the in-shoe sensors, shown in Fig. 1a, are fabricated on 80 µm thick PET (polyethylene terephthalate) with a 7 µm patterned aluminum layer. The insole electrode sheets consist of three sensor channels: two channels for the metatarsal heads and one channel for the heel. The area of the metatarsal heads is divided into lateral and medial metatarsal heads (abbreviated later as lateral MTH and medial MTH). The sensor channel electrodes have a circular shape with a diameter of 18 mm.

The in-shoe sensors were constructed manually by integrating the film-type sensor material pieces between the insole electrode sheets. Three separate in-shoe sensors were fabricated, one for each film-type sensor material (PVDF, CNF and EMFi). First, the signal electrode of the insole electrode sheet was covered with double-sided adhesive foil (JEJE Produkt, Netherlands), from which the sensor channel areas (measurement locations) were removed to obtain contact between the electrode and sensor material. The sensor material pieces (25 mm x 25 mm) were settled on top of the adhesive foil sheet (see Fig. 1a). Finally, the ground electrode of the insole electrode sheet was folded on top of the signal electrode. The total thickness of the in-shoe sensor is around 0.25 mm. Fig. 1b shows an example of the fabricated in-shoe sensor (PVDF).

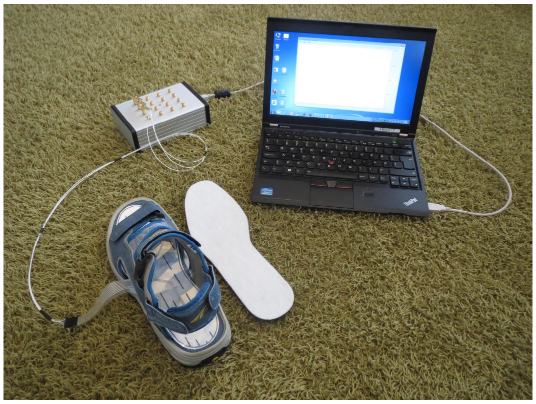

Figure 1. The measurements system.

The measurement system consists of an in-shoe sensor (PVDF, CNF or EMFi), a charge amplifier and a 16 bit AD-converter measuring the charge generated by the in-shoe sensor. The connection to the AD-converter from the in-shoe sensor was provided via coaxial wires and crimp connectors (Nicomatic Crimpflex). Fig. 2 illustrates the measurement system components.

IV. MEASUREMENTS

Before the actual plantar pressure distribution measurements, the sensor sensitivities and crosstalk between the sensor channels in each in-shoe sensor were measured. The piezoelectric sensitivity of each in-shoe sensor type was measured using a dedicated measurement setup [7, 26]. Briefly, the sensors are excited with a mechanical shaker providing a dynamic sinusoidal input force and the charge generated by the sensor is measured. The sensitivity is defined here as the charge generated by the sensor divided by the normal force used to excite the sensor (unit C/N). This is closely related to longitudinal piezoelectric coefficient d_{33}. The longitudinal d_{33} coefficient describes the electric polarization generated in the same direction as the stress applied [27]. The piezoelectric sensitivity of each material was measured for each sensor channels separately (lateral MTH, medial MTH and heel). The sensitivity in each location is an average of five repetitive measurements.

Crosstalk between the sensor channels was determined by exciting one sensor channel at a time with the dynamic sinusoidal force and measuring the outputs of all sensor channels. The crosstalk is calculated here by dividing the sensor channel signal amplitudes with the excited sensor channel signal amplitude.

For the plantar pressure distribution test measurements, each in-shoe sensor was located inside a shoe (shoe size EU 44), one at a time and covered with an insole, shown in Fig. 2. To measure the plantar pressures and evaluate the plantar pressure distribution, five separate single steps were measured with PVDF, CNF and EMFi in-shoe sensors from a test subject (male, height 183 cm, body weight 90 kg).

V. RESULTS

Table I shows the sensitivity measurement results for each sensor materials. The results are shown as the mean sensitivity ± standard deviation of five measurements in each measurement location (lateral MTH, medial MTH and heel). The EMFi in-shoe sensor had the highest sensor sensitivity values, (175.0 ± 32.5) pC/N. The lowest sensor sensitivity values were measured with the CNF in-shoe sensor ((0.9 ± 0.3) pC/N). The sensitivity of the PVDF in-shoe sensor was (16.2 ± 1.8) pC/N.

TABLE I. SENSITIVITY MEASUREMENT RESULTS (UNIT PC/N).

Sensor material	Lateral MTH	Medial MTH	Heel
EMFi	166.0 ± 4.6	142.4 ± 5.9	216.6 ± 6.8
PVDF	15.9 ± 2.7	16.3 ± 1.2	16.4 ± 1.6
CNF	1.1 ± 0.3	1.0 ± 0.2	0.7 ± 0.1

For the EMFi in-shoe sensor, crosstalk from 9.0 % to 20.4 % was measured. For the PVDF in-shoe sensor the crosstalk was about 10 %. In the case of the CNF in-shoe sensor, the crosstalk could not be determined due to the low signal levels and measurement noise.

Fig. 3 shows the examples of the measured plantar pressure distribution signals. The signals are shown as charge signals (unit pC), not actual pressure signals. As seen in the figure, the medial MTH channel of the PVDF sensor and the heel channel of the EMFi sensor are overemphasized. In the case of the EMFi sensor, the higher sensitivity of the heel channel may explain this. With the CNF sensor, the signals between the sensor channels have a rather similar shape. The reason for this may be a crosstalk between the sensor channels even though the crosstalk could not be determined in the crosstalk measurements. The differences between the sensor materials are further discussed in the following Section.

VI. CONCLUSIONS

Nowadays, the measurement of plantar pressure distribution is well established as an important technique for identifying feet that are at risk of ulceration [10]. In this study, we have developed simple in-shoe sensors measuring the plantar pressure distribution. The in-shoe sensors have three sensor channels (lateral MTH, medial MTH and heel) and they are based on film-type sensor materials. Three film-type sensor materials are tested and compared (PVDF, CNF and EMFi).

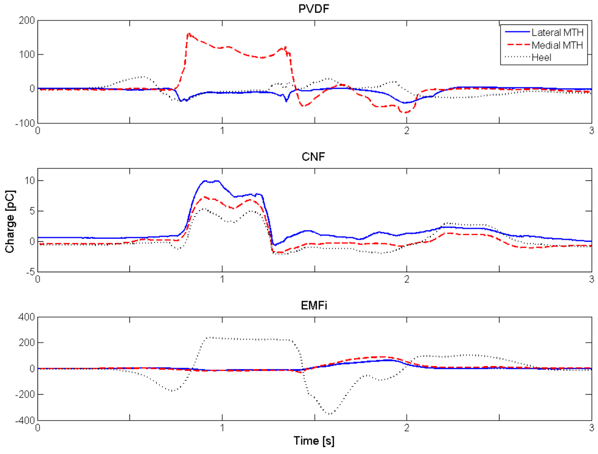

Figure 3. Examples of measured plantar pressure distribution signals.

The in-shoe plantar pressure measurement provides a challenging measurement environment for the sensor. Several challenges are associated with the in-shoe measurement, such as crosstalk between elements, error due to the bending forces and the difficulty of calibration [1]. A high sensitivity and linearity as well as a low hysteresis of a single sensor are essential in order to ensure accurate and reliable plantar pressure recordings [13]. The sensor should also be robust and have a minimal effect on the distribution of forces [6]. Cavanagh *et al.* describes the inside of the shoe as a ‘hostile environment’: it is warm, damp and contoured when compared with a flat walking surface [10].

With the piezoelectric film-type sensor materials, thin and flexible in-shoe sensors can be fabricated. The sensors can be easily integrated in laminated structures and there is no need for auxiliary energy (generator-type sensor). These properties can be seen as advantages. However, piezoelectric sensors do not measure static force and only the change of a force can be measured (dynamic force). In addition, piezoelectric materials exhibit also pyroelectric response and for this reason they can be difficult to use in conditions where the ambient temperature varies [14].

Each film-type sensor material tested in this study has its pros and cons that should be considered when using the sensor material in plantar pressure distribution measurements. For instance, the PVDF material is also sensitive to forces in transverse directions (piezoelectric coefficients d_{31} and d_{32}). If the mechanical stress is applied to more than one mechanical axis of the PVDF material simultaneously, the output voltage is formed by the stress components on these axes. The different stress directions cannot be separated from the signal when a single sensor layer is used. Previously, Kärki *et al*. have utilized this property and developed a four-layer PVDF sensor measuring all the stress directions (normal stress and anterior-posterior and medial-lateral components of shear stress) [7]. As for the EMFi material, it has very high sensor sensitivity and it’s not as sensitive to bending forces as the PVDF material. In addition, the pyroelectric response of the EMFi material is weak [28]. The CNF material, instead, is a low-cost and bio-based material that has potential for mass-manufacturing of disposable piezoelectric sensors. The CNF material, however, is a new sensor material and a lot of research and development has to be done. For instance, the CNF sensor used in this study first had signal strengths comparable with previous study (sensitivity 5-7 pC/N) [23]. After a few initial test steps, the sensitivity decreased to the level presented in Table 1. The compression of CNF material under the high weight is a possible explanation. Based on this finding, it seems that this type CNF film is too soft and fragile for the high forces appearing in the plantar pressure distribution measurements. Thus, further studies to improve the film properties are ongoing.

The operation of the developed in-shoe sensors was evaluated here through piezoelectric sensitivity and crosstalk measurement as well as the plantar pressure distribution measurements. The sensor sensitivity measurements with the PVDF and EMFi in-shoe sensors provided results comparable with the values given by the manufacturers. However, since the sensor material is sandwiched between the electrodes, the contact between the sensor material and the electrode may not be as good as in the case of electrodes processed directly on the sensing material. This may reduce the sensitivity and add variation in the sensitivity results. The crosstalk measurements revealed crosstalk between the sensor channels with the PVDF and EMFi materials. Plantar pressure distribution measurements also suggest crosstalk between the CNF sensor channels. The common ground electrode of the sensor channels or capacitive coupling between signal channel wirings may increase the electrical crosstalk. The laminated electrode structure may increase the mechanical crosstalk. The amount of crosstalk can be seen as a disadvantage.

In plantar pressure distribution measurements, each sensor material provided similar results inside the set of measured steps. However, some differences between the in-shoe sensors based on different sensor materials were observed. The differences mainly arise from the material differences discussed previously in this Section. Still, a typical pattern with two peaks in pressure distribution exists during walking and can be seen in every in-shoe sensor signal shown in Fig. 3: the first peak reflects the heel strike and the second peak is in the forefoot.

To conclude, simple, flexible and easy-to-use in-shoe sensors based on film-type sensor materials were developed and tested in this study. Even though the results were promising, further research is still needed to fully utilize the materials in plantar pressure distribution measurement. The main objective here is to use the in-shoe sensor in the prevention of pressure ulcers. For this application, more measurement locations and sensor channels would be useful. In addition, the location of measurement sites should be more carefully considered. Also other application areas for the sensor are available, e.g. rehabilitation and sports.

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