Sensors and Actuators A 246 (2016) 91–101

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Design, fabrication, and characterization of a compliant shear force sensor for a human–machine interface

A. Chaykina*, S. Griebel, L. Zentner

Technische Universität Ilmenau, Mechanism Technology Group, Max-Planck-Ring 12, 98693 Ilmenau, Germany

ARTICLE INFO

Article history:
Received 5 November 2015
Received in revised form 30 March 2016
Accepted 13 April 2016
Available online 22 April 2016

Keywords:
Decubitus ulcer
Shear force
Compliant sensor
Silicone elastomer
Internal pressure
Electrical contact

ABSTRACT

The determination of shear forces acting on a body is of crucial importance in decubitus ulcer prevention. The commercially available shear force sensors are generally costly and due to their properties (compliance, design of the deformation element, etc.) often unsuitable for this specific application.

In this paper we propose and characterize the principle of a novel compliant shear force sensor for use in an anti-decubitus system. The sensor consists of conductive and non-conductive silicone elastomers, and includes a hermetically closed cavity which is continuously supplied with an internal pressure. The dependence of the distance between the two conductive sensor components (1) on the acting shear force and (2) on the internal pressure allows the magnitude, and the direction of the shear force to be determined by measuring the internal pressure when opening or closing the electrical contact.

The sensor principle was characterized by analytical calculation and finite element method (FEM) analysis. Finally, the functional model was evaluated with metrological tests. Thereby, it was supplied with an internal pressure ranging from 0 to 0.045 MPa in 0.005 MPa increments and simultaneously loaded with a shear force. Depending on the pressure and the direction in which the shear force was applied, the minimum shear force required to activate the detection circuit was in the range 2.6–6.8 N. The determined sensor characteristic showed a high linearity ($R^2 > 0.998$).

1. Introduction

The main factors causing the decubitus ulcer (also known as a pressure ulcer or bedsore) include long duration pressure whose effect is increased by shear forces. These shear forces cause a shift of skin layers against each other or even their separation from each other [1–3]. The application of shear force sensors on the interface between a human body and a bed surface or seat should help to ensure that the shear forces can be identified and eliminated in time.

Akins et al. [4] quantified interface shear stress for commercial wheelchair seat cushions. The reported interface shear stress varied from 0.8 to 14.9 kPa. Thereby, a vertical load of 51 ± 1 kg and a horizontal displacement of 0, 10, 15, and 20 mm was applied to the cushion. Sakuta and Takahashi [5] have shown that the shear stress of 0.9 N/cm^2 (9 kPa) might be equivalent to the pressure of 50 mmHg. A further criterion known from the state of the art is that at a shear stress of roughly 100 g/cm^2 (9.8 kPa) the pressure to produce occlusion is half of the required value [6]. According to studies by Kosiak [7] the pressure of 60 mmHg produced edema, cellular infiltration and extravasation after only one hour. Based on the information above the shear stress from 9 to 14.9 kPa can be relevant for investigation and prevention of decubitus ulcer. The required measuring range of the shear force sensor can be determined by multiplying the shear stress and its corresponding sensing area.

Force sensors, known from the state of the art, usually consist of two main sub-components: sensor elements for energy conversion (for example, piezoresistive [8–14], piezoelectric [15,16], capacitive [17–19], optical [20–22], or inductive [23] sensor elements) and of devices for transmitting the force to the sensor elements (force transmitting mechanisms respectively deformation element). Most of the known solutions include rigid elements and do not provide high deformability. In such cases, the lack of compliance is addressed by embedding the sensor elements and force transmitting mechanisms in a flexible substrate [8,9,11,18]. This embedding process leads to additional costs, because the highly elastic materials have to be bonded with less elastic materials. Furthermore, the rigid components of the sensor can interfere with the shear force distribution exerted by a person on a seat or bed surface. In addition, a completely compliant version is prefer-

* Corresponding author.
E-mail address: alexandra.chaykina@tu-ilmenau.de (A. Chaykina).

http://dx.doi.org/10.1016/j.sna.2016.04.034
0924-4247/

able for reasons of minimizing the risk of injury and improving the comfort at the human–machine interface.

The key challenge in the development of compliant sensors for a human–machine interface is that they must be inexpensive, and have sufficient elasticity. One possibility for the development of compliant sensors is provided by silicone elastomers. These are commercially available with a range of mechanical properties, and may be conductive or non-conductive. The inclusion of a sufficient quantity of electrically conductive filler material, such as carbon black, increases the conductivity of the composite. Such composites have extensive uses as tensile or compressive force-sensitive electrical conductors. This enables simple new solutions for the development of a compliant sensor [24–27].

In [28], a compliant multi-axial sensor based on silicone elastomer is described. The sensor consists of a silicone elastomer layer, which contains three channels filled with a liquid metal and a rigid plastic force-post. The force-post deforms (compresses) the channels depending on the magnitude and direction of the acting force, resulting in the increased electrical resistance of the channels. The sensor satisfies the requirements for compliance, but due to elaborate manufacturing process it is complicated to produce. Moreover, only three channels positioned at an angle of 120° are used to determine the shear force direction, as a result of which the force action direction can be estimated imprecisely. It is an open topic of investigation whether this sensor can be applied in a lying or sitting area because of its measuring range. The sensor encompasses a shear-sensing area of 50 mm × 60 mm and is validated for in-plane force of 0–1.1 N by the manufacturer. Consequently, for a shear stress from 9 to 14.9 kPa, the shear force caused will range from 27 to 44.7 N. Thus, it considerably exceeds the tested range of the sensor.

In this paper we present the design, the functional principle, and the fabrication method of a novel compliant shear force sensor. Furthermore, we also characterize the sensor principle using analytical, numerical, and metrological investigations.

The sensor has a shear-sensing area of 314 mm^2, hence the required measuring range of the sensor for shear stress mentioned above is of 2.8–4.7 N. Our sensor was tested for up to approximately 7 N. Thus, the sensor is suitable for similar investigations as described in [4] for a horizontal indenter displacement greater than 20 mm.

The proposed sensor is simple, inexpensive, consists of commercially available highly elastic materials, and due to its execution in an anti-decubitus system can be used for the detection of shear forces acting between the surface and the body.

2. Sensor operating principles

2.1. Sensor operating principles

Fig. 1 shows the sensor design. The sensor consists of one elastic touch element, one elastic deformation element, and n electrodes (n = 1, 2, 3...). All of these are positioned on a base plate. The elastic touch element is connected to the deformation element and to the base plate in an airtight manner and forms a cavity. Via an air supply, it is possible to change the compressed air p in the cavity. n electrodes are arranged at the same radial distance around the deformation element's longitudinal axis and at an angle $\beta = 2\pi/n$ to this. In what follows, we consider the case $n = 4$ and thus the angle $\beta = \pi/2$. The electrodes allow a displacement in the z-direction, whereby the distance a_E between the touch element and the electrodes is adjustable (Fig. 1(a)–(d)).

The touch element and the electrodes are conductive elements. If a shear force is applied, the deformation element will be distorted (see Fig. 1(e)). This results in a change of distance a_E between the reversibly deformable touch element and the corresponding electrode j. There is a minimum force $F^*_{\text{shear,min}}$ (threshold value) from which these two elements contact each other and, thus, close the electrical circuit. A non-zero voltage V_j (where j = 1...4 is the number of electrode) can subsequently be detected across the corresponding resistor R_j. Furthermore, in all other circuits without contact the voltage V_j is equal to 0 V. If the internal pressure p increases, the contact closed with electrode j will be opened again (see Fig. 1(f)). The acting shear force can be determined by measuring the internal pressure p_j at the moment the contact opens. The threshold value $F^*_{\text{shear,min},\,j}$ is set by the distance $a_{E,\,j}$ and can be selected as a different value for each electrode j. In this paper we consider the case that the distance $a_{E,\,j}$ and thus also the threshold $F^*_{\text{shear,min},\,j}$ are equal for each electrode.

It is also possible to measure shear force by means of the closing of the contact. For this, before the shear force determination the internal pressure p should be chosen to be high enough that while a shear force is acting, no contact is closed. The voltages V_j to be measured are then equal to 0 V. If the internal pressure p is slowly released, at a certain value of pressure an electrical contact will again be realised between the touch element and the electrode. Thus, a non-zero voltage V_j can be detected through the electrodes' closed circuits.

The dependence of the shear force, which closes or opens the electric circuit, on the internal pressure p results in the sensor characteristic $F^*_{\text{shear},\,j}(p)$. The individual contributions of the shear force are then determined using the sensor characteristic curves $F^*_{\text{shear},\,j}(p)$ of the respective electrode. The resultant shear force is calculated according to Eq. (1):

$$\vec{F}^*_{\text{shear,res}} = \left(F^*_{\text{shear,1}}(p_1) - F^*_{\text{shear,3}}(p_3)\right)\vec{e}_x + \left(F^*_{\text{shear,2}}(p_2) - F^*_{\text{shear,4}}(p_4)\right)\vec{e}_y \quad (1)$$

The vectors $\vec{e}_x$ and $\vec{e}_y$ in Eq. (1) are the basis vectors. They represent the direction (x and y respectively) of the calculated force. In this case, by means of electrode number 1 (j = 1) and pressure p_1, the magnitude of the shear force component $F^*_{\text{shear,1}}(p_1)$ in the positive x-direction is determined. The magnitude of the shear force component $F^*_{\text{shear,2}}(p_2)$ in the positive y-direction is determined via electrode number 2 (j = 2) and p_2. The magnitudes of the shear force components $F^*_{\text{shear,3}}(p_3)$ in the negative x-direction and $F^*_{\text{shear,4}}(p_4)$ in the negative y-direction are measured accordingly via electrode number 3 (j = 3) and p_3 and via electrode number 4 (j = 4) and p_4 (see Fig. 2).

The angle φ is calculated from Eq. (2).

$$\varphi = (1 - \Phi(F^*_{\text{shear},1}(p_1)))\cdot\pi + \arctan\frac{F^*_{\text{shear},}\ 2(p_2) - F^*_{\text{shear},4}(p_4)}{F^*_{\text{shear},}\ 1(p_1) - F^*_{\text{shear},3}\ p_3)} \quad (2)$$

with the Heaviside function according to Eq. (3):

$$\Phi\left(F^*_{\text{shear,1}}(p_1)\right) = \begin{cases} 1, \text{ if} F^*_{\text{shear},\ 1}(p_1) \geq 0 \\ 0, \text{ if} F^*_{\text{shear,1}}(p_1) < 0 \end{cases} \quad (3)$$

Fig. 2 shows a plan view of the sensor under the influence of shear force from different directions as well as diagrams with respect to the voltage–pressure curve. In the diagrams, the voltage–pressure curve is indicated by an arrow and the abbreviation CO (for Contact Opening) and CC (for Contact Closing).

If a shear force acts in the direction $\varphi = 0$ (see Fig. 2(a)), it comes to the contact closing of the inner wall of the touch element with electrode 1. A change in the voltage V_1 can be detected. The circuits of electrodes 2, 3, and 4 are not closed. The corresponding voltages V_2, V_3, and V_4 are equal to 0 V. By increasing the internal pressure p (according to the arrow with abbreviation CO), the contact with electrode 1 will be opened at pressure p_1. Then, the magnitude of the shear force F^*_{shear} can be determined using the sensor characteristic curve $F^*_{\text{shear,1}}(p)$.