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Development of a smart fabric force-sensing glove for physiotherapeutic Applications

Abstract: In this work, a low-priced smart fabric force-sensing glove is developed which is able to measure the total amount and direction of the force a person applies on a patient in a physiotherapeutic context. A device like this would be beneficial for the education of physiotherapists, to measure the progress of a patient and to evaluate the treatment.

The proposed device uses a new sensor, which is based on a piezoresistive fabric. This fabric changes its electrical resistance according to the applied stress. The characterization of this sensor revealed that the change in resistance of the sensor is dependent of the amount of force, the loaded area, the total time the sensor is loaded and hysteresis. To compensate these behaviours, an additional sensor based on the same smart fabric was developed which measures the loaded area of the first sensor. By combining these two sensors, it is possible to calculate the applied force.

The results show the feasibility to build a measurement system out of smart fabric material that can measure the applied force. Furthermore, the prototype shows promising results in determining the applied force in amount and direction.

Keywords: smart fabric, physiotherapy, force sensor, sensor glove

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1 Introduction

An improvement step in orthopaedic recovery processes would be the treatment by a physiotherapist, providing quantifiable and objective measurement options. E.g. one could provide the patient with an objective visualization of his healing process, by continuously monitoring the returning strength in an injured body part and could therefore provide

an objective assessment of the condition of a patient.

A measuring device capable of improving these issues should be applicable in a treatment context, such as consist of materials that do not irritate the patient or influence the tactile sensation of the physiotherapist. It should be able to provide useful measurements such as the amount and the direction of the applied force. Furthermore, the device must be cheap in production, as an expensive measurement device would be an unjustifiable financial burden for a physiotherapist and therefore impede an expansive distribution.

2 Related Work

There is a variety of different devices available, both commercially and as scientific prototypes, that try to quantify the movement and sensations of the human hand.

The *Tekscan™ Grip System®*, based on FSR technology, consists of a flexible foil, which is wrapped around the hand. It covers a wide measuring range and offers a high spatial resolution but is very expensive and is not able to determine the direction of the applied load. Other available products as the *Applied Fitness Glove* and *Pinch Glove* by *Virtual Realities Ltd.* also include FSR sensors at the palm, respectively the fingertips. In the *X-IST Glove HR3* by *NO-DNA* bend sensors are additionally installed. These devices are too expensive, only a part of the inner hand surface is covered with sensors and most of the devices stated above are not able to determine the direction of the applied load.

Many scientific prototypes also rely on the FSR technology to measure load [1–3]. FSR sensors are cheap, easy to use and limited flexible, properties which fit the requirements. On the other hand, they have an unchangeable surface and their signal is influenced if they are not mounted on a flat surface.

There are also scientific groups [4, 5], which use a smart fabric based sensor to instrument a glove. They use varying smart fabrics, which change their electric properties when loaded. *Büscher et al.* [5] developed a smart fabric sensor based on a piezoresistive fabric by *Eeonyx®* and applied 54 of these sensors on a glove. Due to their textile structure, they are much easier to implement into a glove and the surface can be adjusted to fit the shape of the human hand. However,

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those sensors show difficult hysteresis and drift characteristics [5]. The developed prototype of *Büscher et al.* is not able to calculate the applied force.

3 Methods

In this work, we introduce a concept, which is based on the same principle and a fabric from the same company as *Büscher et al.* used. The proposed load sensors signal is combined with a hand motion capturing system and other sensory devices to develop a concept, which is able to measure the amount and direction of applied forces. Using smart fabric textiles, it is possible to develop a sensor, which has low construction height, does not interfere with the tactile sensation of the user, is flexible and can easily be integrated into a glove. The proposed sensor consists of a piezoresistive fabric called *EeonTex™ NW170-PI-20* by the company *Eeonyx®* and two layers of the conductive fabric *Shieldex® Technik-tex P130+B* by *Statex* (see Figure 1). Both textiles are inexpensive compared to commercially available solutions. In the following, this sensor will be described as load sensor. The piezoresistive fabric is placed between two layers of conductive fabric and this system is sewn together. The proposed sensor changes its electrical resistance when loaded, due to the amount of force applied and the size of the loaded area. Thus, it is necessary to estimate the loaded area to be able to calculate the applied force. Therefore, a second area sensor is proposed which is based on the same principle. In contrast to the first proposed sensor it has not one active area, which covers the whole sensor surface, but three small active points implemented with crossovers of a small diameter copper wire (see Figure 1). Under each load sensor an area sensor of the same size is placed which allows one to determine, whether one, two or three thirds of the surface of the load sensor above is loaded. These sensors can measure loads, which act orthogonal to their surface, but this setup is not capable of measuring transverse loads. Overall 30 instances of this combined sensor are placed on different spots on the inner side of the hand (see Figure 1). The respective position is selected, so that the user is able to move his hand without restrictions. In particular, the motion axes of certain hand segments as well as the finger joints are not instrumented, to prevent excessive bending of the sensors. To measure the amount and direction of the combined force of all these sensors, one needs to know the position of these segments relatively towards each other. This can be done by measuring the angles between the segments. Therefore, on the backside of the hand eleven bend sensors are applied, which change their resistance when deflected.

Figure 1: Visualization of the proposed concept

We used commercially available sensors called *Flex Sensor* by *spectrasymbol®*. Two bend sensors are placed on each finger, one over the metacarpophalangeal joint and the other one over the proximal and the distal interphalangeal joints, as proposed by *Popov et al.* [6].

Table 1: Parameters for the different trials

Trial	Course	Loaded Area	F max	Time t1
1	1	1 cm ²	50 N	24 s
2	1	1 / 3 / 5 cm ²	50 N	24 s
3	2	1 cm ²	50 N	120 / 24 / 13,3 s
4	2	1 cm ²	5 / 25 / 45 N	24 s

It is possible to estimate the movement of the two interphalangeal joints with one sensor, because they move dependent on each other during grasp movements [6]. An additional sensor is placed crosswise from the back of the hand towards the thumb to measure the adduction of the thumb, as proposed by *Fang et al.* [7]. Based on calibration data it is possible to calculate the angle between the segments with the measured resistance change in the bend sensors. Using the described sensors and the resulting information about load, area and position it is possible to calculate the applied force. The sensor data is recorded by a microcontroller with a 16-bit AD-Converter and a voltage divider with a built-in resistor of 200 Ω . A multiplexing circuit is switching between the different sensors and allows a consecutively measurement of all sensors. This setup results in a sampling frequency of 5.3 Hz per sensor, which

Figure 2: Schematic view of the different load courses

Figure 3: Resistance over pressure load depending on the size of the loaded sensor area

could be increased using a A/D Converter with a higher sampling frequency.

The development of the load sensor unit revealed a strongly non-linear characteristic, which requires additional analysis steps. The characteristics are determined using a *Zwick® - Z050* which applies load on the sensor and collects the relevant parameters (amount of force and resulting deformation) with a sample rate of 100 Hz. The load is applied with a stamp with a defined contact area. The resistance change is measured and collected with 100 Hz by a *NI™ myDAQ* Acquisition Card with a 16-bit A/D Converter and the same measurement circuit mentioned earlier. Each of the following trials is performed five times, subsequently the average is used to analyze the characteristics. All of the presented trials are executed in a load spectrum from 0 to 50 N/cm². Trial 1 investigates the repeatability and hysteresis of the sensor (see Figure 2 “Course 1” and Table 1). Trial 2 investigates the dependence of the sensor signal on the size of the loaded area, by performing the same trial with three different stamp sizes and the same pressure. The stamp sizes correspond to the smallest, respectively the largest size of a single sensor built into the glove sensor (see Figure 2 “Course 1” and Table 1). The effect of constant load on the sensor signal is determined with the trials 3 and 4 (see Figure 2 “Course 2” and Table 1)

4 Results

During trial 1 the resistance of the sensor changes from 1,5 kΩ in an unloaded state to 44 Ω when loaded with F max. For repeatability, the standard deviation of all five trials is about 2% of the mean for the whole measurement range.

Generally, the sensor has a higher resistance for the same amount of load when the load is increased, than when the load is decreased. Concluding, the sensor has a significant amount of hysteresis. The relative difference between the

Figure 4: Relative deviance over time loaded depending on different amounts of time t1

sensor output signal for increasing load to decreasing load has an amount of 50% for a very small load and decreases linearly down to 0% at F max.

The results of the second trial showed that the sensor signal is dependent on the loaded area (see Figure 3). Using eq. 1, where N equals the number of samples measured during one trial, S1 is the set of samples of the trial with 1 cm² and SX is the set of samples of the trial with 3 cm² respectively 5 cm², the mean relative difference P between the 1 cm² and the 3 cm² respectively the 5 cm² trial was calculated with an result of 3.07 or respectively 4.84.

$$P = \frac{1}{N} \sum_{i=1}^N (S1_i - SX_i) \quad (1)$$

The output signal of the sensor seems to be inversely proportional to the amount of the loaded area. The results are plausible when compared with an idealized electrical replacement circuit of the used smart fabric. Under the assumption that the fabric consists of evenly distributed fibers, which change their resistance when compressed, the fabric can be considered to be a parallel circuit of potentiometers. Because the same pressure was applied over different areas, all loaded fibers are expected to change their resistance by the same amount. During the different trials, the number of compressed fibers would be three respectively five times higher. The resulting resistance R_{res} can be calculated using

$$\frac{1}{R_{res}} = \sum_{i=1}^N \frac{1}{R_i} \quad (2)$$

with N equals the number of potentiometers and R_i the resistance of the single potentiometers. Therefore, R_{res} of the stamps with size 3 cm² or 5 cm² is $\frac{1}{3}$ or $\frac{1}{5}$, respectively of R_{res} using the stamp with size 1 cm².

The third trial is shown in Figure 4 respectively in Figure 5. Pictured is the course of the signal during the 30 s of unchanged load. To illustrate the changing sensor signal, the relative deviance of the measured resistance after t1 + X seconds and the resistance measured at the time t1, is computed. Therefore, the resistance measured at t1 seconds

Figure 5: Relative deviance over time loaded depending on different maximum loads $F_{\max}$

equals 100%. One can deduce that a varying total amount of load $F_{\max}$ results in a similar course of the signal, while a varying time t_1 results in different signal courses (see Table 1). This behavior indicates that the signal is decreasing slower when the total time under load is increased. Creeping effects in materials show a similar trend over time, which leads to the assumption that the used smart fabric is subjected to creeping effects which result in more compression over time which in turn results in a reduced amount of electrical resistance.

5 Discussion and Conclusions

The results of the characterisation show the complex behaviour of the proposed smart fabric load sensor. However, they seem plausible when analysed with an electrical replacement circuit. Büscher *et al.* [5] achieved similar results characterising a piezoresistive smart fabric by *Eeonyx*[®] regarding the hysteresis and repeatability. Open research questions are the influence of fast changing dynamic loads on the sensor signal, the influence of the environment temperature, the influence of other mechanic parameters like bend and tensile load and the influence of humidity.

Based on the identified behaviours it is possible to calculate the force, using the information of the load, area and bend sensors. The finished prototype as well as an exemplary calculation of the force are shown in Figure 6. However, the current sample rate is only suitable for quasi-static loads and should be increased. Other possible improvements are the fabrication, which is complex and time consuming, as well as increasing the spatial resolution of the area sensor.

The presented prototype is a first step towards the intended goal. The usage of smart fabric materials allows one to build an affordable measuring glove that meets the requirements. The characterisation of the load sensor and the integration of

Figure 6: Finished prototype with an exemplary force calculation

the position and area sensing sensors enables one to calculate the force. Initial trials show promising results.

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