Capacitive Insole Sensor for Hip Surgery Rehabilitation

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Abstract— **We are developing a capacitive insole sensor in order to measure the force between foot and an insole. The sensor is intended to guide a hip surgery patient to train the operated leg with a suitable force. In this paper, we propose a flexible, laminated structure for a capacitive force sensor matrix. The preliminary measurements indicate that the sensor could be used as a limit detector to sort out too light and too heavy steps. We have also evaluated our method comparing our sensor signal to the signal measured with a commercial force transducer. Finally, we have made long-term measurements in order to evaluate the stability of the capacitive sensor elements.**

Keywords - capacitive; force sensor matrix; rehabilitation; insole

I. Introduction

Rehabilitation after hip replacement surgery requires the patient to train to use the operated leg again. At the beginning, the operated leg can not support the full weight of the body and for this reason some patients are scared to place any load on the operated leg, which is harmful for the recovery. In general, humans have difficulty in estimating how much weight they set on the leg while they are walking with a cane or crutches. For this reason there is a need for a device which is able to measure the force that is set on the operated leg and sort out too heavy and too light steps.

Wearable sensors systems that measure force between foot and an insole or shoe have various medical applications. Bamberg et al. have tested force resistive sensors to assess balance [1]. Morley et al. have tested a system that measured the temperature, humidity, and pressure on a shoe in order to warn patients with diabetes about possible skin breakdowns [2]. Capacitive methods measuring force in a shoe has been tested by Kothari et al. [3]. Piezoelectric films like polyvinylidene fluoride (PVDF) and Electromechanical Film (EMFi) has been also tested in gait analysis applications to convert dynamic force between foot and a shoe into an electric signal [4,5].

The insole sensor prototype presented in this paper is a part of a Tekes (Finnish Funding Agency for Technology and Innovation) funded project that is aiming to develop a wearable sensor system to support rehabilitation after hip surgery. The system monitors the position of a patient's legs and hip with sensor nodes that include 3-axis accelerometers and 2-axis magnetic sensors. The system also measures the force between foot and a shoe with a capacitive insole sensor. In the future, the insole sensor is planned to be integrated into a shoe with the sensor node, a power source and a wireless link.

The main purpose of the designing and construction of the insole sensor prototype was to study structure and functioning of a flexible capacitive force sensor matrix. The insole sensor was intended to use as a limit detector that is able to differentiate too light or too heavy steps. For this reason, a rather simple structure was developed. One of the leading ideas of this design was that there is only one patterned conductor layer and no manual assemblies for single sensor elements are needed. The layers of the insole sensor are just laminated together. This reduces manufacturing costs.

This prototype was built to gather test data and aid the development of signal processing methods. If the signal processing is simple enough, it will be programmed into the microcontroller of the sensor node. This would be ideal because sending out capacitive matrix data over a wireless link wastes power. It is intended that the limit values for too heavy or too light steps could be programmed into the sensor system by stepping on a scale or holding foot and insole in the air.

II. Methods

A. *Stucture of Capasitive Insole Sensor*

The capacitive sensor elements of the insole are formed when a 5 mm thick EPDM rubber sheet and conductive fabric layers are laminated over the electrode pattern and wirings on a flexible PCB (Figure 1). The sensor's layers were attached together with silicone sealant. The top conductive fabric layer is used to mediate a high frequency stimulus signal to all capacitive elements. The EPDM sheet is used as a dielectric material that deforms when force is directed at sensor element, thus altering its capacitance. The electrodes and wiring on the flexible PCB mediate the signal to readout electronics. The conductive fabric layer under PCB shields electrodes against EMC.

There are 8 capacitive elements in the insole sensor. Their positions in the insole are presented in Figure 2. Four of them measure the force under the heel area and four elements are placed under the ball of the foot. The diameter of one element

This work was supported by Tekes (Finnish Funding Agency for Technology and Innovation).

PERVASIVEHEALTH 2008, 30 Jan - 1 Feb. Tampere, Finland

DOI 10.4108/ICST.PERVASIVEHEALTH2008.2510

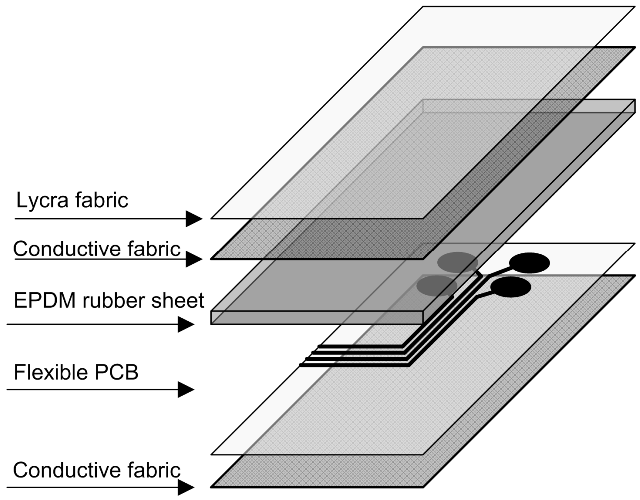

Figure 1 The exploded view of the insole sensor. The capacitive elements are made of conductive fabric, EPDM rubber and flexible PCB.

is 17 mm. There are also two dummy wires along the wires that are used to probe capacitive elements. They are used to compensate the distortion signal that is picked up by the actual wirings.

B. Read-out Electroniscs

The insole and read-out electronics were placed on a sandal (Figure 3). The integrated capacitance-to-digital converter (CDC) is used to sense capacitances in the insole. The type of CDC is AD7142 (Analog Devices). The capacitive elements of the insole are connected to the CDC with a 10 cm long 13-wire cable that is made of a flexible PCB. The CDC is placed along with the other needed electronics on the sandal strap above the instep. An ATmega168-microcontroller is used to program and control the CDC. In the present version the microcontroller is connected to a PC with a cable but in the future it will be replaced with a wireless link.

C. Signal Prosessing

In this application, we are interested to know the total force that burdens the operated hip when the person walks. Unfortunately, we can not measure this quantity directly with a wearable system. Instead we are estimating the force between a foot and the insole with a capacitive force sensor matrix. At the moment all values relative to capacitances are recorded and the value estimating the total planar force is calculated by using Matlab program after the actual measurement. The algorithm that is used is simple and it is intended to program into microcontroller in the future in order to calculate the total force practically in real time and to warn the patient.

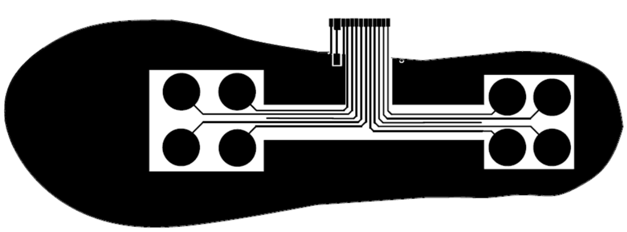

Figure 2 The place of the capacitive elements on the flexible PCB. There are four elements under the area of heel and 4 under the ball of the foot. There are also two dummy wires that are used to compensate the distortion picked up by wiring and cables.

Figure 3 During test measurements, the capacitive insole sensor was placed in a sandal with read-out electronics.

In total there are ten capacitance values available for the total planar force calculations. Four of the values represent the force on the heel and four on the ball of the foot. Two values estimate the distortion that is picked up by the wirings. At first, the offset values of each channel are removed from the signal by subtracting the value that is received when the insole is not loaded. The offset values are different each instance of use. Next the dummy wire value that represents the interference signal picked up by the wirings and the distortion of capacitances in the heel area is subtracted from the values that are relative to the force on the heel. After that, all heel force values are added together. A similar procedure is done to the values of the ball of the foot. The sum of the ball of the foot values is multiplied by two. This compensates the fact that if the same force is set on the heel and the ball of the foot, in case of the ball of the foot force is distributed to larger area. Finally, we get an estimate value for the total force by summing up the weighted values**.**

D. Test Procedures

The usability of the insole sensor and the developed signal processing method was tested by finding out if they can be used as a rehabilitation aid in order to differentiate too light and too heavy steps. In this test, the insole sensor was used to help test subjects to learn how to set force corresponding to a 30 kg weight on their leg. At the beginning of test subject were asked to wear the sandal with the insole sensor and hold their foot in the air. Then test subjects were asked to step on scales so that it indicated weights of 20, 30 and 40 kg. Test persons were instructed to distribute their weight as evenly as they can between the heel and the ball of the foot. The values that were received with steps of 20 and 40 kg are used as the limits for too light or too heavy steps. Next test subjects were instructed

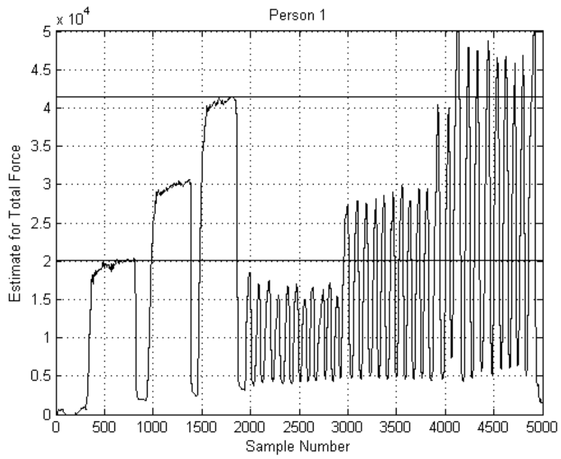

Figure 4 The estimate signal for the total force between foot and the insole during step test performed by the test person one. The solid horizontal lines indicate the limits for too light or too heavy steps.

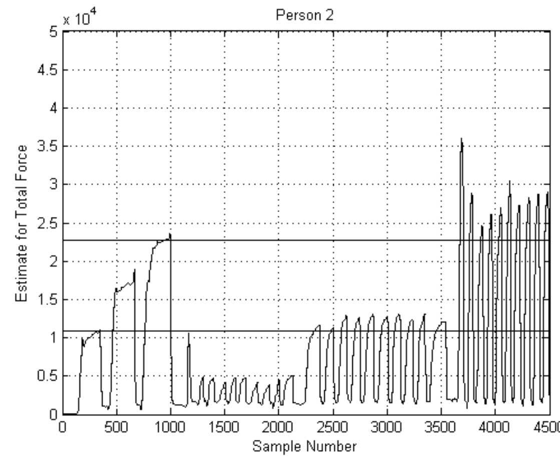

Figure 6 The estimate signal for the total force between foot and insole during step test performed by the test person two. The solid horizontal lines indicate the limits for too light or too heavy steps.

to step on the scale with weight less than 20 kg, about 30 kg and over 40, 10 times each.

The insole sensor's ability to follow dynamic force changes was tested by comparing the estimated total force signal to a signal of the Tecsis 3550 force transducer. This reference transducer was installed between two rigid plates and the test subject stepped on the plates while wearing the insole sensor. The test subject tried to alter the force of his steps. Before actual test, an adjustment value was recorded by stepping on a scale with a force corresponding to 40 kg in order to convert the force estimate signal into kilograms.

Weight is moving from heel to the ball of the foot and back while a person walks. This might affect the method when evaluating the total force that is set on foot. For this reason the functioning of our method was tested while subject walked forward. At first the test subject took a few normal steps. Next he took a few steps with a cane in order to lighten the weight

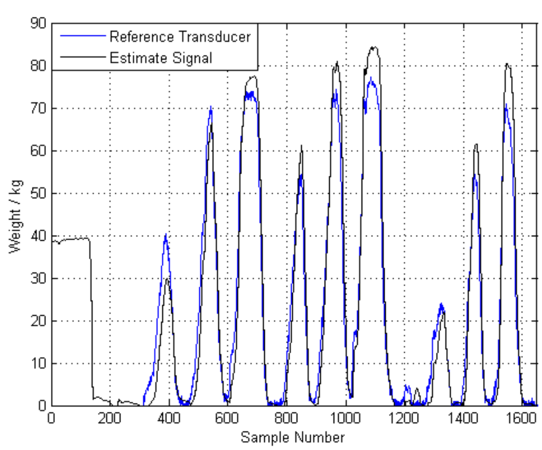

Figure 5 The estimate signal for the total force was compared with the reference force signal while a test person stepped on the reference transducer with varying weights. At the beginning of the signal there is an adjustment step which is used to convert the estimate signal into kilograms.

that was set on the leg. The mass of test subject was 80 kg.

In rehabilitation application the insole sensor should work several hours without any adjustments. Stability of the capacitive sensor element may deteriorate because of humidity and the compression of the dielectric material. For this reason the drifts of the capacitive elements were measured during a 4-hour test period. The insole sensor was worn in office environment during a workday and unloaded values relative to capacitance values were recorded every half an hour.

III. Results

The estimates for the total force between a leg and insole during step tests performed by test subjects one and two are presented in figures 4 and 6. The signal of third test person is more or less similar. At the beginning of signals, there are three adjustment steps. Next there are about 30 test steps. The horizontal lines in figures 4 and 6 indicate the limit for too light and too heavy steps. They are drawn according to 20 kg and 40 kg adjustment steps.

According to this preliminary test data and by using corresponding 20 kg and 40 kg limits we can sort out 97 percent of too light steps and 90 percent of too heavy steps. All steps intended to be about 30 kg stay between limits. The test subjects found it hard to control the weight of their steps within a few kilos. For this reason, first steps of subjects 2 and 3 were heavier than they intended.

The signal of the reference force transducer and estimated total force signal are presented in Figure 5. Both signals are converted into kilograms. The estimate signal is scaled into kilograms by using 40 kg adjustment step value at the beginning of the signal.

The estimated force while the test person is walking is shown in Figure 7. After an adjustment step, there are 4 normal steps and the next 4 steps with a cane. In order to evaluate how the weight is moving between the heel and the ball of the foot corresponding signals are also presented. The force estimate is converted into weight by using an adjustment step.

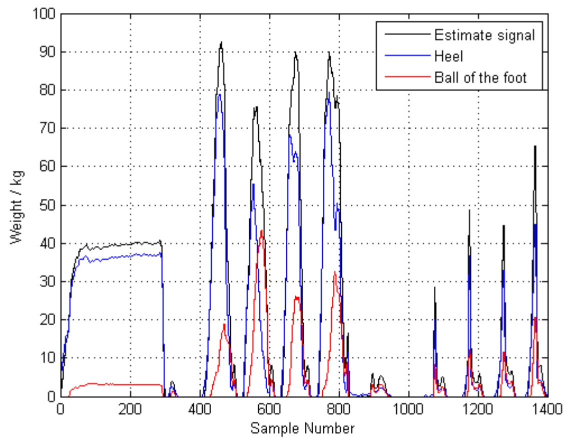

Figure 7 An estimate signal for the total force converted into kilograms according to 40 kg adjustment step at the beginning of the signal. There are 4 normal steps and 4 steps where subject has lightened steps by using a cane.

The drifts of the capacitive element values under heel and ball of the foot area were measured during a 4-hour test period. The drifts of dummy wire values between capacitive elements were also recorded. In Figure 8 the average signal drifts of corresponding elements and dummy wires are presented as a change of the output value of the CDC. In this test, the elements under heel area are drifting more that the elements under the ball of the foot.

IV. Discussion

The amplitude of the estimated total force signal is not same between test subjects because the weight of a person is not distributed to capacitive elements in the same way. This can be explained by the fact that subjects may have feet with different shapes and they can place their foot at a slightly different position on the insole when they wear the sandal. According to this preliminary data, the presented method of estimating the total force and adjusting force limits seems to adapt to different persons and the results justify further development.

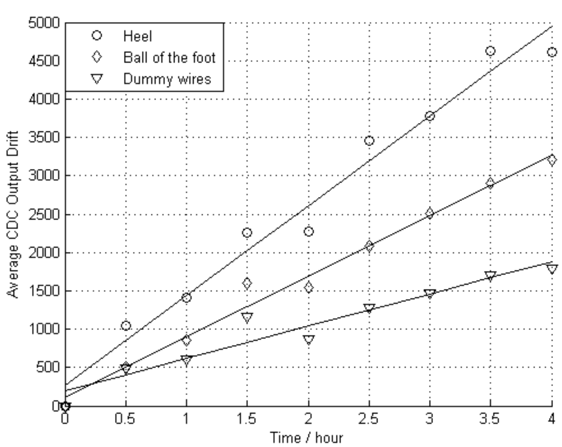

Figure 8 The average drift of the capacitance of the sensor elements presented as CDC readings during a 4-hour test period.

When the estimated total force signal is compared with the reference force signal, it can be shown that the insole sensor is able to follow reference signal rather well even if the weight of steps is altered. The insole sensor reacts to dynamic force fast enough to be used to measure the force of a step. In this data, the maximum difference between the sensor reading and the reference values is about 10 kg. This may be too much for if the sensor is used as a scale. On the other hand if the sensor is used as a real-time limit detector to help a person to notice far too light or far too heavy steps, the uncertainty of measurement is not that severe. That is because a human can not control the weight that is set on a leg very accurately and it is hard to specify which weight would be optimal.

According to preliminary measurements our method of estimating the total force seems to give reasonable results while a test person is walking forward and the difference between normal and lightened steps is clear. The results of the drift test indicate that our method of evaluating the total force and set force limits with adjustment steps will fail without offset drift compensation.

V. Conlusion

In this paper, we presented a laminated structure for a capacitive insole force sensor and a signal processing method that can be used to estimate the total force that is set on a leg while a person is walking. The present version of the insole sensor can be used to record 8-channel force data. The total force is calculated afterwards by using Matlab program. Far too light or heavy steps could be sorted out with a limit detector. The drift of the capacitance values is a problem during long-term measurement. In the future we will make our sensor wireless and try if it is possible to compensate the drift by measuring unloaded capacitances between steps

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