ELECTROCUTANEOUS FEEDBACK SYSTEM TO IMPROVE THE ESTIMATION OF PRESSURE APPLIED TO THE FOOT

Jan Walter Schroeder, Venketesh N. Dubey
Smart Technology Research Centre, School of Design, Engineering & Computing
Bournemouth University, Poole, Dorset, U.K.

Tamas Hickish
Royal Bournemouth and Poole Hospital and Bournemouth University Dorset, U.K.

Jonathan Cole
Poole Hospital NHS Foundation Trust, Poole, Dorset, U.K.

Keywords: Biomechanics, Sensory loss, Piezoresistive sensor, Artificial sensation, Electrocutaneous feedback, Chemotherapy, Diabetes.

Abstract: Peripheral neuropathy can result from diseases such as diabetes and also chemotherapy for cancer. This sensory loss can result in numbness and impairment of gait and balance. An electrocutaneous feedback system might help these patients to overcome these problems. The idea of such a device is to equip a shoe insole with force sensors that can detect pressure. The signals received by the sensor are processed and amplified in a suitable form and are redirected to an appropriate area of skin more proximal on the limb via an electrocutaneous feedback systems. In this work a low cost prototype is presented that represents a full functional electrocutaneous feedback system. The prototype uses 4 piezoresistive sensors that are placed on the insole of a shoe. The force sensors can detect the pressure that is applied to the foot. The electrocutaneous feedback is given through electrical pulses. The pulse amplitude and repetition frequency is fixed while the pulse length is controlled with the amplified signal for sensory feedback.

1 INTRODUCTION

Peripheral neuropathy can result from different disease such as diabetes, infections or after chemotherapy. Patients who suffer from this condition have limitations in their daily life due to the lack of sensory feedback from their extremities. The loss can result in impairment in gait and balance. It is difficult for these patients to feel the force that they have to apply to a certain object, e.g. the gas pedal of a car. An electronic insole with a user friendly interface may help those patients to improve their daily life conditions. The idea of such a device is to equip a shoe insole with force sensors that can detect pressure. The signals received by the sensor are processed and amplified in a suitable form and are redirected to an appropriate area of skin more proximal up the limb via tactile stimulation. These tactile stimulators can be an arrange of types including vibration (Jeonghun, 2003), reinervation (Kuiken , 2007), air pressure (Asumara, 2002) or electrical stimulation (Matjevic, 2008). In this study the latter is studied in more detailed because of its effectiveness and low costs. An economic prototype for artificial sensing with low-cost components is presented.

1.1 Sensation of Pressure

To feel the sensation of pressure when it is applied to the dermis, the second layer of the skin, has sensory nerve endings located very close to the first layer to the epidermis. Skin can be seen as a viscoelastic media that deforms when touching something (Maheshwari, 2008). This deformation affects the neuron nerve endings, as an active sensor

Schroeder J., N. Dubey V., Hickish T. and Cole J..
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DOI: 10.5220/0003167503860390
In *Proceedings of the International Conference on Biomedical Electronics and Devices* (BIODEVICES-2011), pages 386-390
ISBN: 978-989-8425-37-9

for touch, under the epidermis. Neurons transmit sensing signals as well as muscle stimulating signals by using chemical ions to produce an electrical charge that moves along the neuron, the action potential. The information arrives as a sensing signal to the brain where it is processed.

Several diseases can cause damage to the nerves which is called peripheral neuropathy. Some of these diseases are listed below:

- Leprosy
- Diabetes mellitus
- Idiopathic polyneuropathy
- Toxic (Alcohol, other toxics)
- Infection illness (Typhus, HIV)
- Cancer patients (Chemotherapy)

Different patterns of peripheral neuropathy affect different parts of the body while the most common one is peripheral polyneuropathy, which mainly affects the feet and legs. Symptoms of peripheral neuropathy encompass loss of sensing and other feedback sensations.

1.2 Force Sensor Technologies

A force sensing device is mainly composed of two elements. The force-sensitive element produces a signal according to a physical stress while the data-acquisition element receives the signal and collects the data for further analysis. Besides micro-electro-mechanical based systems, there are several sensors that work at a molecular level and convert mechanical stress into an electrical signal. The deformation of a piezoelectric material leads to the generation of a voltage potential and flow of current that can be measured. The voltage is proportional to the force applied to the sensor. (Maheshwari, 2008), (Cotton, 2009), (Arshak, 2005).

Piezoresistive sensors are made up of metals and semiconductors and change their resistance on deformation. (Hollinger, 2006) Piezoresistive sensors were found suitable for different biomedical applications. A high sensitivity to deformation is important for force sensors that are used in biomedical applications. The piezoresistive sensors show this behaviour (Herrera-May, 2009).

1.3 Electrical Stimulation

Electrical Stimulation is widely used in medical diagnostics and treatment. (Zhang, 2007), (Sheffler, 2007). A pair of electrodes is applied to the skin and current flows from one electrode to another. The current can be alternating current (AC) or direct current (DC) and is defined by its three criteria: Current, frequency and pulse length Stimulus current is usually in the range of 10 mA to 100 mA for clinical treatments, while the stimulus voltage is usually in the range of 10 V to 100 V or more (Robertson, 2006).

At a suitable frequency of variation (intensity or direction) a nerve impulse or muscle contraction occurs. For this purpose up to 100 Hz are used. But also higher frequencies are used in the range of 1 kHz to 10 kHz. At frequencies higher than this nerve and muscle fibres cannot respond.

The nerves which are close to the electrodes are more affected to the stimulation. As a consequence if low current density stimulation is applied to the skin, the nerve fibres which normally respond to touch and pressure, are the first to be stimulated. With higher current density nerves which are located more deeply, like the muscle fibres, can be stimulated.

The shape of the signal also plays a role in the stimulation of the nerves.

For most application a rectangular stimulus is optimal, because the nerve fibre can accommodate to the current of non rectangular signals. As a result the generation of an action potential is not likely, because the threshold for a trigger event is not reached.

Transcutaneous Electrical Nerve Stimulation (TENS) is often used to describe wearable devices with pulsed current in the range of 1 to 120 Hz and a pulse duration of about 50-200 micro sec.

1.4 Electrocutaneous Feedback Systems

Lundborg et al. use piezoresistive sensors applied to the fingertips to transfer sensations to the upper arm by the use of skin electrodes (Lundborg, 1998). Experiments in a set-up of five test subjects showed that different pressure levels can be discriminated with the help of the electrical impulses that were transferred to the upper arm. In their following research work they tested audio signals as a force sensor feedback. The differentiation of fingers and applied forces showed satisfying results.

Matjacic et al. (2000) developed a two-dimensional electrocutaneous feedback system for use in paraplegic standing. Their results indicated that feedback signals could be interpreted after a certain learning period.

2 MATERIALS AND METHODS

Based on the literature search and comparison of different available technologies for tactile sensing, the piezoresistive technique was identified as the most suitable for the purpose of integration into an artificial sensing device that is adjusted to patients needs concerning weight and usability.

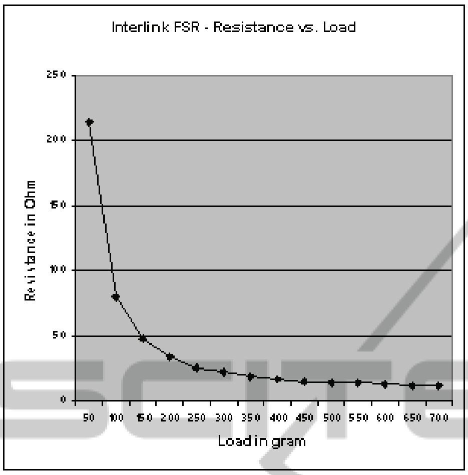

Figure 1: Resistance vs. Load for Interlink FSR.

2.1 Sensor Calibration

Figure 1 shows the calibration measurements that demonstrate the behaviour of resistance of a piezoresistive sensor against load which is proportional to the force applied to the sensor.

The conductivity σ of the sensor is linear because it is direct proportional to the reciprocal of the resistance R and therefore suitable for the purpose of transferring a feedback of the force as an electrical stimulation to sensing skin, because the conductivity can be amplified linearly.

Another calibration test was the comparison of different sensors to define their deviation to each other when load is applied. The arithmetic mean µ and average deviation δ were calculated.

Table 1: Deviation test for 7 force sensor devices.

Load in g	**µ of R in kΩ**	**Max. δ**	**Max. δ in %**
50	26.89	0.14285	5.18
300	259.07	-17.06767	-6.59

Table 1 shows that the deviation for different sensors and two loads of 50 grams and 300 grams was at 6.59% maximum which was found to be suitable for test purposes. However, the information received by the sensor producer was that different piezoresistive sensors can have a deviation up to 50%. Therefore it might be necessary to calibrate every single sensor before it can be implemented in an electronic insole.

2.2 Components

For the construction of the sensing system four commercial force sensors of the type LuSense PS3 are used (Figure 2-B).

The current source is a standard 9 Volt battery. The main components in the circuit design are an operational amplifier and a pulse width modulator (NE555), (Figure 2-A).

The transformer that was used is a Miniature Audio Transformer LT700.

The link between the transformers and the skins are electrodes of the type Ambu Neuroline 700.

3 RESULTS

3.1 Prototype Design

A first prototype giving electrocutaneous feedback was designed. Figure 3 shows the schematics of the design. The Sensor Unit of the prototype consists of 4 piezoresistive force sensors. The force sensors detect pressure that is applied to the foot. An operational amplifier helps to amplify the sensor response. Since the conductivity of the output is linear the voltage received by the operational amplifier is directly proportional to the pressure applied to the sensors.

The Pulse Creation Unit creates a pulse with a fixed frequency and amplitude. The pulse in the Pulse Creation Unit has a frequency of 50 Hz. The maximum amplitude of the pulses is about 100 V. The Pulse Creation Unit uses the output of the Sensor Unit to modulate the pulse width of the pulse proportional to the output with a pulse width modulator. The pulse lies within a range of 50-200 µs and is dependent on the amplified signal of the Sensor Unit. The pulse controls a transformer which is part of the Electrical Stimulation Unit. The transformers amplify the pulse from the Pulse Creation Unit and transfer the pulse through electrodes to the skin. The loop that is connected to the skin is galvanically isolated from the controlling circuit.

3.2 Preliminary Tests

A preliminary test showed that the feedback system gives electrocutaneous feedback in the areas where the electrodes are attached. The stronger the

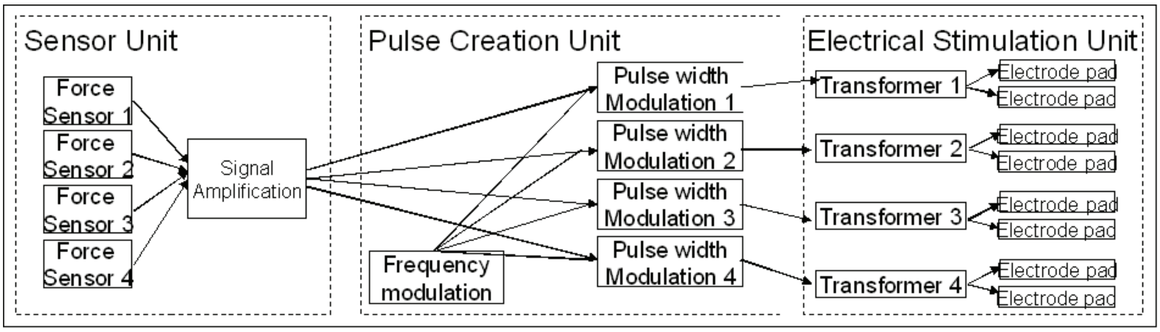

Figure 2: Circuit board (A) and Sensor Unit (B).

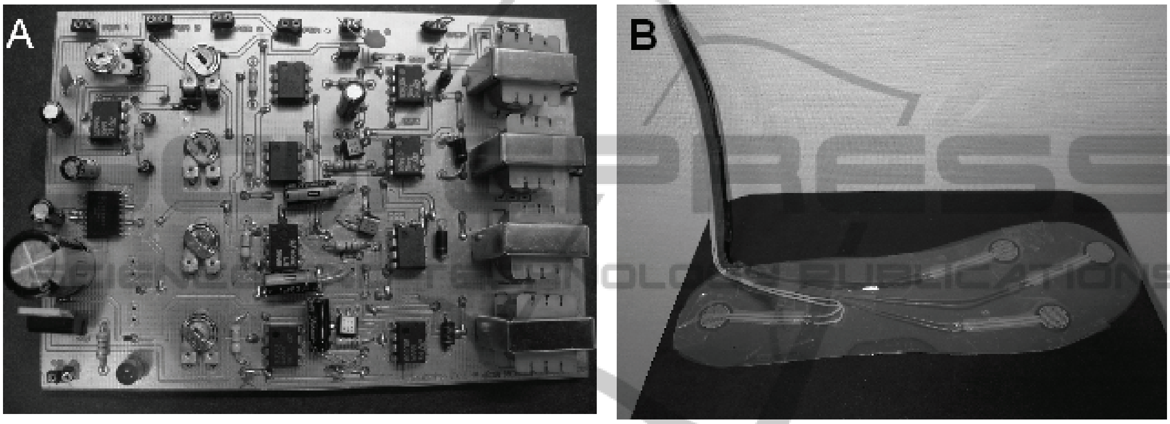

Figure 3: Schematic of the prototype.

electrodes are pressed the stronger the electrocutaneous feedback is. In a first test it was possible to differentiate which sensor was pressed. Figure 4 shows the pulse that is applied through the electrodes for a minimum load of 50 g. Figure 5 shows the pulse that is applied through the electrodes for a maximum load of 1 kg. The shape shows the behaviour of the skin that is acting like a capacitor that is charged and discharged.

The maximum Voltage is 90 Volt represented on the y-axis. The length of the pulse represented in the x-axis is 100 µs at minimum load and 140 µs at maximum load and the frequency is 28 Hz.

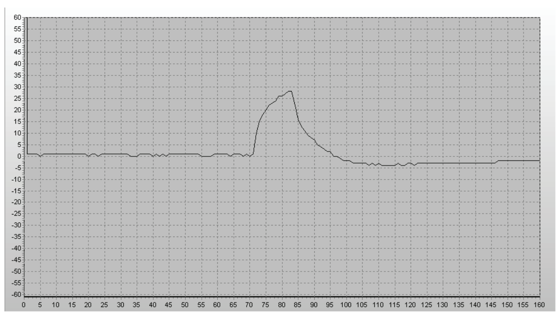

Figure 4: Shape of pulse on the electrodes measured with minimum load.

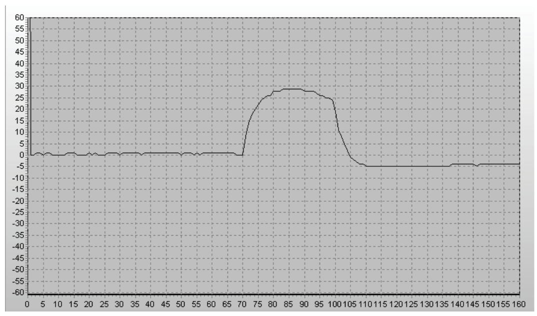

Figure 5: Shape of pulse on the electrodes measured with maximum load.

4 CONCLUSIONS

A low cost electrocutaneous feedback system was developed and a prototype was presented. The components of the prototype are standard materials with low costs. In a preliminary test the feedback system showed encouraging results. The feedback is linear to the applied pressure on the foot, since the pulse width changes proportional to the applied applications. The presented design has the potential to be applied to real patients and help them to improve their daily life.

However certain improvements can be made to make the device more suitable for clinical purposes. The pulse form could be changed to an alternating form, since a non alternating pulse can cause toxic reaction under the electrodes because of accumulating ions under one of the electrodes. However for testing purposes direct current can be used since the time of current flowing is not very long.

The acceptance of the skin to electrical stimulation is also nonlinear. If a microprocessor is integrated into the design an intelligent processing of the sensor data is possible. This would improve the feedback. The research group presenting this paper is currently working in processing the data from the Sensor Unit in an intelligent way using knowledge based systems.

The next step in our research will be the development of a more flexible system that is taking into account the points mentioned above. It is hoped that patients suffering from sensory loss can have an enormous improvement in their daily life when using an electrocutaneous feedback system, so they can better walk, balance and perform tasks that require the estimation of pressure applied to the foot.

ACKNOWLEDGEMENTS

The authors want to thank Angel Torres Perez and Adam Wright for their help in the design and the manufacturing of the circuit board, as well as Poole Hospital to provide the facilities for the testing.

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