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Functional shoe for the detection of walking pattern anomalies

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Functional shoe for the detection of walking pattern anomalies

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Abstract. Analysis of walking patterns can play an important role in the diagnosis of musculoskeletal disorder and detecting anomalies in walking gaits. In this work, we introduce a systematic approach to detect person's walking patterns. A flexible resistive pressure sensor, developed from electro-conductive textile fabric, is non-intrusively integrated in an ordinary shoe together with a time of flight height sensor. The constructed shoe detects both the pressure between shoe and foot and the gap between shoe and ground. The combination of those give a trace of the walking pattern. The shoe should be functional in detecting walking pattern anomalies.

1. Introduction

Several diseases are characterized by problems with walking. One of these is Parkinson's disease (PD), which is a disabling pathology affecting millions of people of all races and cultures globally. The characteristic motor features of the disease include bradykinesia (i.e. slowness of movement), tremor, rigidity (i.e. resistance to externally imposed movements), flexed posture, postural instability and freezing of gait [1]. The primary biochemical abnormality in PD is a deficiency of dopamine due to degeneration of neurons in the *substantia nigra* [2].

For some Parkinson's patients, the lack of dopamine may cause irregular and asymmetrical walking patterns. These are caused by the tailing behind of one leg due to unequal intensity of the neurological signals. In the worst-case scenario, the patient trips and falls as a consequence of the irregular walking pattern. PD affects about 1% of the population over the age of 60 years [3], a figure that is expected to double by 2020 [4].

To detect the irregularity, a 'smart shoe insole' was designed, including sensors capable of analyzing the walking pattern of the wearer. In case of pattern anomaly, the shoe can warn the wearer and further prototyping can show how actuators could be integrated to prevent falling. An alternative application for the shoe could be aiding in avoiding toe-walking in children or adults, by giving an appropriate feedback to help remember to walk in a flat-footed fashion [5]. Such feedback could be for example a vibrating motor, which has already been used to notify people of bad sleeping habits [6]. In figure 1 an

example of the difference between a regular and an irregular walking pattern is given. Detecting the irregularity of the step can augment other wearable sensors used for diagnosis and treatment [7].
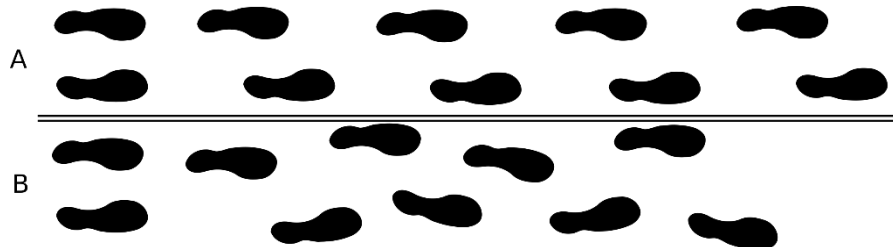

Figure 1. Comparison of a regular walking pattern (top) with an irregular walking pattern (bottom).

2. Material and Methods

Different ways can be used to evaluate a person's walking pattern. In this project, two sensors are considered for integration into a shoe: a textile pressure sensor to detect when the foot exerts pressure onto the shoe, and a distance sensor to measure the distance between the shoe and the ground or the distance to the opposite leg while walking. The registered data provide insight into the wearer's walking pattern, and a baseline for benchmarking can be set up and hence anomalies can be detected. Extra useful information can be collected by an accelerometer which is readily available in several wearables.

Standard thin pressure sensors are common now, but not textile based. They are typically thin film pressure sensors [8], and though easy to use, not ideal to combine with textile material.

A flexible textile pressure sensor was constructed in several ways. A first sensor is constructed by separating two conductive, stainless steel (SS) fabrics (the electrodes) with a non-conductive barrier fabric, and connecting electrical wires to the stainless-steel fabrics by soldering them via connectors as previously developed by some of the authors [9]. This design concept and working principle is shown in figure 2. When enough pressure is applied to the top of this system, surface fibres of the conductive fabric are pushed through the barrier fabric, contacting the conductive layer on the other side. This closes a circuit and thus allows electricity to flow, which can be detected by the electronics connected to the circuit.
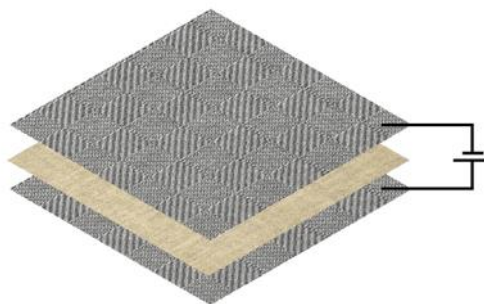

Figure 2. Concept of the pressure sensor: a non-conductive fabric separates the two electrodes which are conductive fabric.

The second and third sensor considered use the same principle but use a commercial non-woven treated with Polypyrrole (PPY-E) of Eeonyx, which acts as a variable resistance sensor under pressure. As this material is difficult to calibrate, using it in the tree layer setup improves the detection as the middle layer creates a binary sensor: it detects pressure only above a certain threshold. If the weight that needs to be detected is larger, a thicker barrier material can be used. PPY-E and PPY-E are used in

sensor 2 as electrodes, while in sensor 3 one electrode is SS while the other is E. Moreover, in sensor 3, the barrier material is cotton lightly coated with PPY, see figure 3.
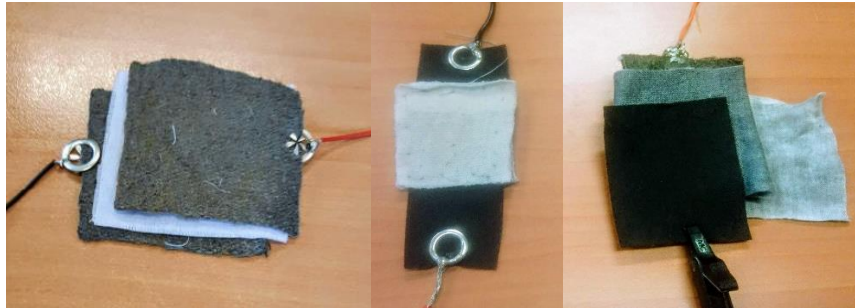

Figure 3. Pressure sensors. Electrodes are, left: SS and SS, middle: E and E, right: SS and E.

Walking creates two main pressure points in a shoe: under the heel where the pressure is highest when the shoe first contacts the ground, and under the ball of the foot where the pressure is highest just before the shoe leaves the ground. For ease of construction the pressure fabric was placed in the heel of the shoe.

As a secondary sensor, a standard distance sensor, was used. We selected the VL53L0X time-of-flight distance sensor. This sensor is laser based and detects distance to surfaces by detecting the reflected wave. We considered two possible manner of placement: directed to the ground or directed towards the opposite leg to detect when it passes.

After a few iterations and analysis of the results we built the final prototype using sensor 3 (SS and E), and with the distance measured as downward as possible. A Wemos D1 mini board is used as data processing unit to read out the sensors. This connects via wifi to a base station, where the results are collected. The pressure sensor is attached to insoles which can be removed and placed in other shoes. Its value is read out with the ADC circuit using a pulldown resistor of 820 kOhm, resulting in ADC values in the range [0, 1023]. A textile connector is used between the insoles and the Wemos board, which is detachable for ease of use. The resulting prototype is given in figure 4.

A drawback of sensors in shoes are the limited place to put the data processing unit and the power source it requires. An alternative solution is to detect walking patterns using accelerometer data from another place on the body, as wearable step counters do attached to the wrist. Ideally for this a place close to the skeleton is used with limited noise from not related movements (like hand waving on the wrist). We put the accelerometer in a belt-bag on the waist as close as possible to the hip bone. We collected data from the accelerometer and analyzed how gait measured via the functional shoe relates to these data. For simplicity a BBC micro:bit was used as it contains an excellent accelerometer.

3. Results and Discussion

The data are validated and used to determine walking pattern irregularity to determine if the approach is viable. The stored ADC values of the textile pressure sensor, and the distance values to the ground are recorded for use in walking pattern analysis. Example processed output is given in figure 5. For normal walking every heel down is clearly registered, resulting in a very good step detection, and allowing steps per minute to be determined. The irregular gait however shows a much more difficult pattern to analyze and extract step data from, however, the clear difference from a normal step can be easily determined. Toe walking on the other hand is clear by a lack of high pressure points.
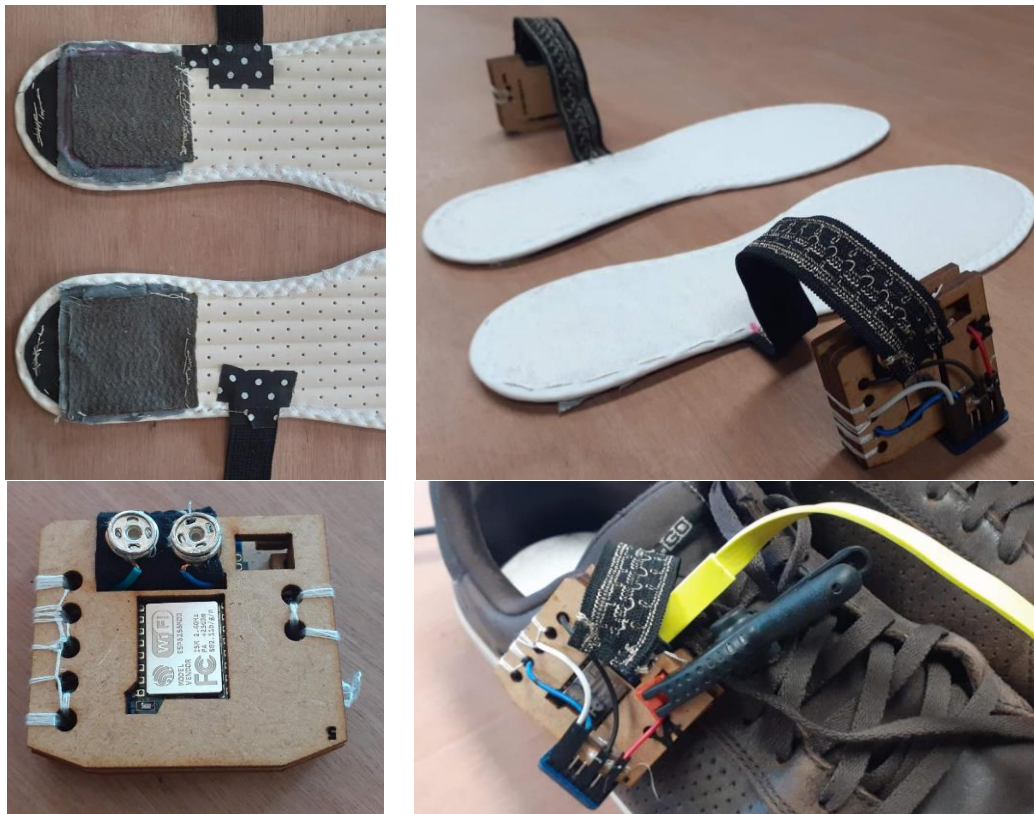
Figure 4. Prototype functional shoe. Left Top: textile pressure sensors at the base of the insole, Right Top: full layout with Wemos board on the side of the shoe, and distance sensor pointing downward, Left Bottom: Wemos board detached, Right Bottom: placement on a shoe for testing.
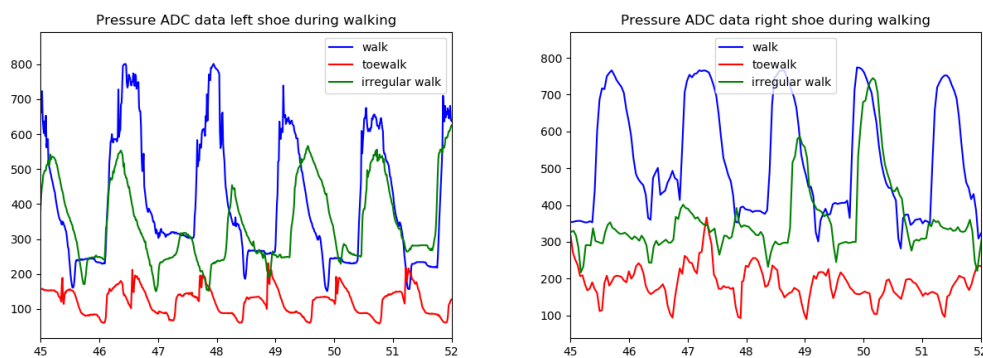

Figure 5. ADC pressure output of left shoe and right shoe showing normal regular walking result, toe walking result and example of irregular gait.

With the data from the left and right shoe, we can clearly determine if the duration of left-foot-down to right-foot-down is equal to the duration of right-foot-down to left-foot-down. Test groups can be set up to compare the measurements from healthy people to those of PD patients in order to validate detection of irregular gait by this method of measurement.

More complex situations would be hard to determine however. Combination with a height sensor has a clear advantage that gaits can be more easily characterized, as is clear from figure 6.
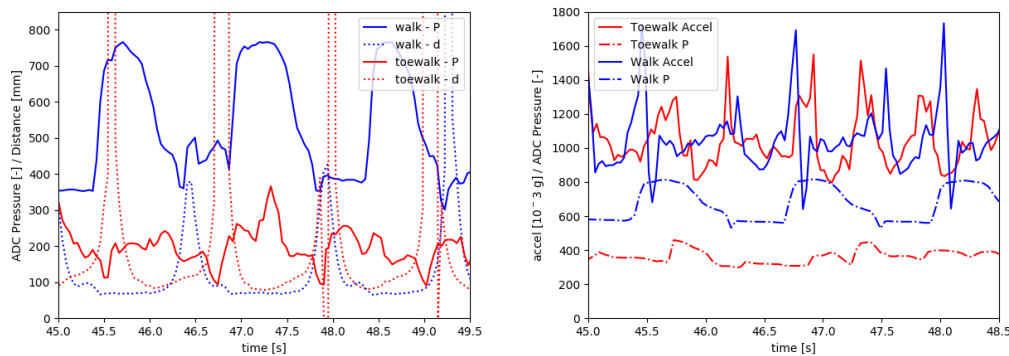
Figure 6. Left: Comparison of pressure data and height measurement at the right shoe. Right: Comparison of acceleration data taken at the right hip and pressure data at the right shoe.

From figure 6 left, we see that first high pressure is detected in normal gait when the shoe is down, while on the lift a peak is found in the distance to the ground. Here it must be noted that due to the rotation of the ankle the height sensor might point to the horizon, leading to infinite distance measure. The height measurement adds little to the pressure data. However, for toe walking where the pressure on the heel hardly changes during walking, the height sensor allows to clearly distinguish steps, augmenting the obtained data from the heel pressure.

In figure 6 right, we compare with acceleration data measured at the right hip. This data is very noisy and would benefit from a smoothing step. Nevertheless, comparing with the pressure data from the heel, it is clear that the peak in acceleration corresponds with the heel down. The following smaller peak in the acceleration data corresponds with the left heel down, which is clearly visible in the acceleration data but almost not present as a feature in the pressure data of the right heel. Again, while the pressure data of the heel makes distinguishing steps for toe-walking almost impossible, the acceleration data shows clear peaks for every foot down, with both left foot down and right foot down peak almost equally large, which was not the case for normal walking.

Our goal of characterizing a 'standard walking pattern' seems feasible using a combination of sensors, though only using one of the three sensors presented should already suffice to know if deviation from the standard walking pattern occurs. Using a textile pressure sensor shows no drawbacks, response times are sufficiently fast and the measurement sufficiently accurate. Next, the data can be further processed. The anomalies would then be detected by software methods. Frequency monitoring would play a big role: how often the wearer steps down onto the ground is the most important factor for an irregular walking pattern, rather than the actual pressure exerted by the foot, or the height the foot is lifted to.

4. Conclusion

We showed that a fabric pressure sensor can be used in step frequency detection, with the data fully matching a distance sensor, and allowing to augment accelerometer data taken at waist height. A further improvement would be to actuate on encountered problems. This would require a constant and real-time comparison of the walking pattern with the aforementioned 'standard walking pattern' by the processing unit. Any significant deviation from this standard pattern would then result in an actuating function of the shoe. Examples of such functions would be the tightening of the shoe grip, vibrations, giving electrical impulses using integrated electrodes that contact the wearer's skin or an app that displays the walking pattern or risk of falling on a smartphone for easy monitoring. Using those actuating functions, the patient would be warned, enabling them to adapt their pace and prevent later problems.

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