Foot Plantar Pressure Monitoring with CYTOP Bragg Gratings Sensing System

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Keywords: Gait Plantar Pressure, Physical Rehabilitation, Polymer Optical Fiber Sensors, Bragg Gratings, CYTOP.

Abstract: In this paper, a polymer optical fiber (POF) sensing solution to monitor the pressure induced in the foot plantar surface is investigated. The paper shows the design and implementation of a platform with an array of 5 polymer optical fiber Bragg gratings (POFBGs) placed in key points to monitor the pressure on the foot surface during gait cycles and the body center mass displacements. The results showed a great response compared with solutions using silica optical fibers. A much high sensitivity and repeatability were achieved using the CYTOP fiber as well as proving that the advantages of POF is a viable and useful solution for this type of application for a future implementation of an integrated "in-shoe" CYTOP POFBGs sensor network.

1 INTRODUCTION

Polymer optical fiber (POF) sensors received high attention recently due to their unique properties compared to the conventional silica optical fiber (SOF) sensors (Webb, 2015). Advantages such as higher flexibility in bending, biocompatibility (Bischoff, 1972), higher failure strain (Large et al., 2009), higher fracture toughness, and lower production cost, are significant for many sensing applications. The lower Young's modulus of POF (Griffiths, 1948) provides enhanced sensitivity to POF sensors when are used for strain, stress and force, pressure, and acoustic wave detection. The material properties of polymers can be chemically modified by adding other organic compounds to achieve specific desirable characteristics. An example is the perfluorinated POF, commercially known as CYTOP, which the carbon-hydrogen bonds have been replaced with carbon-fluorine bonds to reduce the fiber attenuation (Ando et al., 1994). There is an innumerable of applications where POF technology is used (Marques et al., 2017).

On the other hand, the development of efficient solutions for healthcare sensor applications (regarding size, weight and energy consumption) is an important research focus given the rapid technological advances in healthcare monitoring equipment, microfabrication processes and wireless communication (Razak et al., 2012). In that way, the analysis of foot plantar pressure has been investigated by researchers on biomedical applications (Tao et al., 2012; Postolache et al., 2015). For monitoring activities of daily life, an in-shoe foot plantar wearable monitoring system must be efficient, flexible, mobile and low cost. Some of the smart insole implementation based on piezo resistive sensors and wireless data communication modules for walking gait rehabilitation monitoring are reported in (Postolache et al., 2015; Vito et al., 2014). The important features often reported for this kind of solutions are their high resolution data acquisition, free, robust of wireless communication, real time processing and with low power consumption (Postolache et al., 2015). However, electronic devices present some drawbacks, including fragility, long term instability, inconsistency and excessive drift. Additionally, their output is restricted to a small sensing area requiring the use of more sensors to monitor larger areas (Roriz et al., 2014).

The plantar pressure distribution on the foot plantar surface is a reliable and important indicator with regards to foot health condition and gait pattern, from which, information like the wellbeing of the

Vilarinho, D., Theodosiou, A., Domingues, M., Antunes, P., Kalli, K., André, P. and Marques, C.
Foot Plantar Pressure Monitoring with CYTOP Bragg Gratings Sensing System.
DOI: 10.5220/0006533700250029
In *Proceedings of the 11th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2018) - Volume 1: BIODEVICES*, pages 25-29
ISBN: 978-989-758-277-6

spinal cord or regarding the foot ulcerations evolution (in case of patients with diabetes) can be inferred. In the particular case of diabetes, the patients tend to develop foot ulcerations, which can be detected by high/abnormal forefoot plantar pressure (Morag and Cavanagh, 1999). By mapping the ground reaction forces or pressures during gait it is possible to understand the effect induced in the body (Razak et al., 2012).

Many works have been published to explore the plantar pressure distribution but have rarely addressed the application of fiber Bragg gratings (FBGs) on plantar pressure measurement. Also, optical fiber sensing technology has already been used to monitor static plantar pressure values (Hao et al., 2003; Liang et al., 2016; Suresh et a.l, 2015). Nevertheless, till the date, just one reports on dynamic continuous measurements during gait were presented using silica optical fiber technology (Domingues et al., 2017).

In this paper, we propose a fiber-optic sensors network based on CYTOP POFBGs to monitor the plantar pressure. It has the advantages of a simple architecture (only using five sensing elements), relative low cost, temperature insensitivity high stability and sensitivity. Moreover, using polymer fiber technology, it also provides the necessary resistance to be damaged or broken the system during the gait movement as can easily happen using silica optical fiber. It can be used in the measurement of human plantar pressure distribution to monitor and understand whether the foot posture needs to be corrected or not.

2 INSOLE DEVELOPMENT AND RESULTS

The optical platform is composed of a cork sole, with 1.0 cm thickness, in which POFBG sensors will be incorporated in critical points of analysis (heel, midfoot, metatarsal and toe areas, Fig. 1 (a)) to monitor the plantar pressure (Wearing et al., 1999), as shown in Fig. 1 (b). The cork sole was then designed and machined in order to incorporate the network of 5 FBG sensors, which were distributed in the key points for the plantar pressure analysis (heel, midfoot, metatarsal and toe areas) (Razak et al., 2012; Tao et al., 2012), as shown in Fig. 1. The material chosen to embed the sensors was the cork due to its excellent properties for this application, namely thermal isolation, malleability and a near zero Poisson ratio (Silva et al., 2005).

5 FBGs were inscribed and multiplexed into a CYTOP polymer optical fiber cable (Thorlabs, 2017) using point-by-point technique (Theodosiou et al, 2016). In this case, we obtained 4th order gratings from 600 periods making a total FBG length of 1.2 mm. The FBG´s wavelengths range was from 1530 to 1570 nm according with our interrogation system.

Considering the load pressure applied in the gait movement, the FBGs were encapsulated in epoxy resin (Liquid Lens^{TM}) cylinders structures (1.0 cm diameter and 0.5 cm height). Each sensing element consists of such cylindrical epoxy structure with the FBG at the middle position.

To compensate any temperature change, an FBG temperature sensor (Yuan et al., 2012) was incorporated in the insole, in order to guarantee that the thermal isolation provided by the cork is effectively obtained and the FBG plantar pressure sensors are not affected by the body temperature, or any external temperature changes.

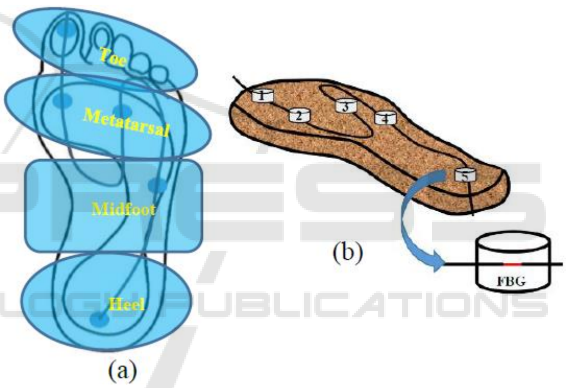

Figure 1: Schematic representation of: (a) the foot plantar main areas; (b) physical distance between FBGs in the CYTOP fiber and the sensors network implemented for the insole.

For the calibration and plantar pressure monitoring, the FBG sensing network was connected to a portable interrogation system constituted of a miniaturized broadband optical ASE module (B&A Technology Co., As4500), an optical circulator (Thorlabs, 6015-3) and an optical spectrometer (Ibsen, I-MON 512E-USB). The latter operates at a maximum rate of 960 Hz, with a wavelength resolution of 5 pm, responsible for the acquisition of the Bragg wavelength shift. Fig. 2 shows the fixed platform monitoring system. To avoid multiple reflections in the final optical spectra, a multimode (MM) fiber was connected between CYTOP and singlemode (SM) fiber before connect to the interrogation system. The array of 5 FBG sensing elements were calibrated to different pressure load values ranging from 10 N up to 150 N. The load sets were applied independently in each sensing point (from FBG 1 to FBG 5), using a probe with a diameter of 10 mm. For these elements, the sensitivity coefficients achieved were 8.31±0.20 pm/kPa (FBG 1), 7.99±0.28 pm/kPa (FBG 2), 8.51±0.23 pm/kPa (FBG 3), 7.71±0.31 pm/kPa (FBG 4), and 8.20±0.15 pm/kPa (FBG 5). Table 1 summarizes all sensitivity coefficients for all CYTOP FBGs.

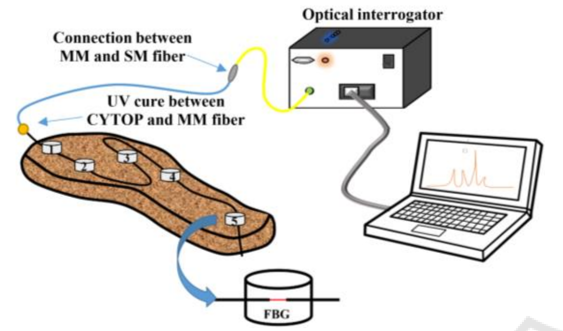

Figure 2: Schematic representation of the fixed platform monitoring system.

Table 1: Calibration of the FBG sensors to pressure.

FBG number	*Sensitivity (pm/kPa)*
1	8.31±0.20
2	7.99±0.28
3	8.51±0.23
4	7.71±0.31
5	8.20±0.15

After the calibration, two sets of studies were implemented in order to verify the reliability of both the fixed platform and the insole developed.

The pressure induced in the sensing elements during a normal gait movement was analyzed with the platform fixed at the ground, as showed in Fig. 3.

Figure 3: Schematic diagram of the protocol implemented for gait analysis using the fixed platform.

The response of each sensing element to the pressure during a gait cycle was repeated and acquired 4 times. The feedback of the platform to the displacement of the body center of mass (BCM) was also evaluated. In Fig. 4, the acquired data is presented, from which it is possible to verify that the sensing network response is similar for the 4 passages, confirming the repeatability of the sensor's response.

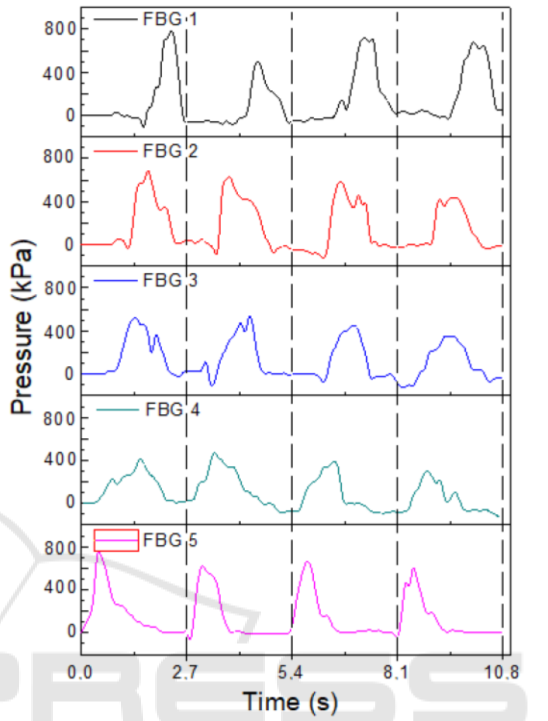

Figure 4: Pressure obtained during the 4 steps and the resulting curve of all the sensors response sum for each step.

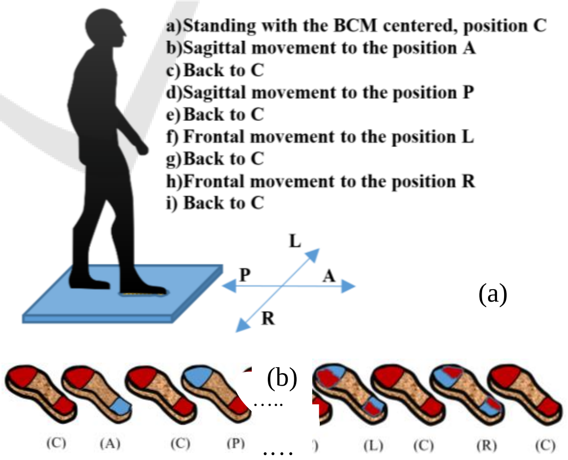

Figure 5: Schematic diagram of the protocol implemented for the analysis of the BCM displacement; b) descritive protocol on the foot (the subject remained in each position for 3 seconds - the pressure on each foot location is colored to red in the scheme).

The BCM displacements, in the body sagittal and frontal planes of motion, were also analyzed using the same platform. For that purpose, a female subject with 55 kg, was asked to place her foot on the sensing platform and to execute a series of BCM movements (with a ~3 seconds duration each), starting by standing still with the BCM centered (C), followed by an anterior (A) position and then back to the original position (C) from which goes to posterior (P) position and then resting again at the center (C). After the sagittal displacement, a frontal displacement was executed, in which the subject moved the BCM first to the left (L), back in the center (C) and then to the right (R), and finally back in the center (C). In Fig. 5, the implemented protocol is schematized.

During the protocol implementation, the Bragg wavelength shift induced in the sensing network was acquired and the correspondent pressures were collected. Fig. 6 presents the response of each sensor, during the different moments of the tests performed.

From the positive feedback of the fixed platform during the performed tests, it becomes evident that the method implemented is an adequate solution for pressure monitoring during gait. Moreover, from the analysis of the pressures registered during the stance phase, it is also possible to infer and monitor the plantar pressures of individuals.

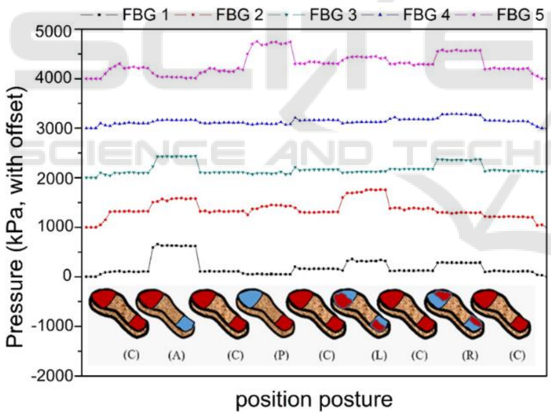

Figure 6: Representation of the pressures detected during the BCM displacements (the pressure on each foot location is colored to red in the scheme).

The main advantages obtained with POF technology when compared with silica fiber technology (Domingues et al., 2017) are the following: much higher sensitivity; high flexibility; easy to handling with fiber when installed to the cork insole where silica fiber breaks many times due to the lack of acrylate protection in the fiber after FBGs inscription.

3 CONCLUSIONS

In this paper, we propose a fiber-optic sensors network based on CYTOP POFBGs to monitor the plantar pressure. It has the advantages of a simple architecture (only using five sensing elements), relative low cost, temperature insensitivity, high stability and sensitivity. Moreover, using POF technology, it also provides the necessary resistance to be damaged or broken the system during the gait movement as can easily happen using silica optical fiber. The measurement of human plantar pressure distribution, to monitor and understand whether the foot posture needs to be corrected or not, was demonstrated in this work. In order to improve the life quality of physically weakened citizens and increase the mobility of elder citizens, an integrated “in-shoe” CYTOP POFBGs sensor network, which is able to monitor health conditions by observing physiological parameters in the foot, is in progress using this technology.

ACKNOWLEDGEMENTS

This work was funded by FCT/MEC through national funds and when applicable co-funded by FEDER—PT2020 partnership agreement under the project UID/EEA/50008/2013. Carlos Marques and Maria F. Domingues acknowledge the financial support from FCT through the fellowships SFRH/BPD/109458/2015 and SFRH/BPD/101372/2014, respectively.

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