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Foot Type Recognition with Multiplexed Optical Fiber Macro-Bend Sensors

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Abstract: The tactile sensing system contains six in-series sensors distributed in order to monitor pressures applied in areas that allow the foot type identification. Principal component analysis was used to infer the system performance.

1. Introduction

The distribution of plantar pressures acting statically when a person is standing, as well as dynamically during a walk or while running, provides useful information, e.g., to evaluate medical conditions or performance of athletes. Knowledge about spatial and temporal parameters of gait, obtained by monitoring plantar pressures, may avoid complications that affect patients with diabetes mellitus [1], or may contribute to understand neurological conditions that impair the motor control [2]. Different plantar pressure patterns can also be assigned to the three main human foot types: flat, cavus and normal [3]. Such information may contribute to an auxiliary diagnosis, as high arch and flatfoot have been associated, in some studies, with lower extremities injuries and back pain [4,5].

Capacitive, resistive, piezoelectric and piezoresistive sensors are used in commercial systems for foot plantar pressure measurements. Commercial platforms or in-shoe systems are usually used for both static and dynamic indoor tests restrict to labs and clinics due to limitations for application in daily monitoring [6]. However, the possible incidence of noise from the electrical equipment connecting data acquisition and processing systems, in addition to the electrical wiring necessary to the proper system operation, constitute some disadvantages of these systems. As an alternative, researchers have proposed the use of optical sensors given some characteristics that overcome the disadvantages cited above, e.g, small dimensions and light weight, immunity to electromagnetic interference and multiplexing capability [7]. In order to address monitoring issues of different physical parameters over a single fiber, a number of multiplexing methods, such as spatial, time-division or frequency division have been proposed [8]. In an attempt to explore favorable characteristics of optical fiber sensors, fiber Bragg gratings [9-12] polymeric fiber devices [13] and bend loss-based systems [13,14] have been used as sensor elements in systems developed for the purpose of plantar pressure monitoring. Seeking for a reliable monitoring system, which can also show other favorable characteristics such as portability, wearability or wireless data acquisition, some authors have developed different optical in-shoe plantar pressure systems [11-14]. Optical fiber sensors based on macro-bend losses stands out when the requirements for the system implementation include the simplicity of fabrication and interrogation.

In this perspective, this paper highlights an application for a multiplexed load sensing array of in-series macro-bend sensors previously reported [15]. Prior tests indicated the system's ability to recognize the application of loads to six in-series optical sensors from their spectral responses. Such sensing system is combined with a pattern classification algorithm based on Principal Component Analysis able to cluster similar foot prints. In the application demonstrated here, it is evaluated the feasibility of identifying different types of human feet with the demonstrated tactile sensing system.

2. Methodology

The plantar pressure measurement system contains six in-series sensor heads, each one consisting basically of an optical fiber loop encapsulated at the center of a cylindrical silicone body with diameter of 21 mm and 7 mm high. Loops with radius of 2.5 mm were produced in standard single-mode fiber (SSMF, G-652, Draktel, 1238 mm cutoff wavelength) and then embedded in silicone elastomer (Dow Corning, BX3-8001). After the silicone cure takes place, the final sensor head has in its interior an optical fiber loop whose plane is orthogonal to the cylinder bases. Each sensor head is installed inside a circular hole drilled in a 5 mm thick insole-shaped acrylic plate, as shown in Fig.1(a). The distribution of the sensing heads in the acrylic plate was chosen in order to monitor pressures statically applied in areas of interest for the foot type identification. Such areas comprise the first metatarsal region, the outside of the arch of the foot and the heel. The system was tested for three foot types (normal, cavus and flat). The acrylic plate provides not only mechanical support for proper sensing heads positioning but also guarantees that each sensor detects pressure exerted exclusively on its surface, in other words, prevents the occurrence of coupled responses. The height of the sensor heads (7 mm), when compared with the thickness of the acrylic plate (5 mm), assures an effective contact between the sensors and the foot, as shown in Figs. 1(b) and 1(c).

Despite SSMF optical fiber was used to fabricate the sensor heads and in the fiber interconnections, modifications in the spectrum transmitted by the in-series sensors are measured in a broad visible spectral range from 400 to 650 nm, therefore, in a multimodal regime. These alterations in the transmitted light are caused by changes occurring in the fiber loop geometry when different pressures are applied on the sensors and they are related to both pure bend losses and light coupling from whispering gallery modes. The interrogation setup uses a broadband white light source (LS-1 Tungsten Halogen, Ocean Optics, FC/PC connectors, black-body spectral irradiance) and a UV-VIS spectrometer (HR4000, Ocean Optics) in transmittance mode.

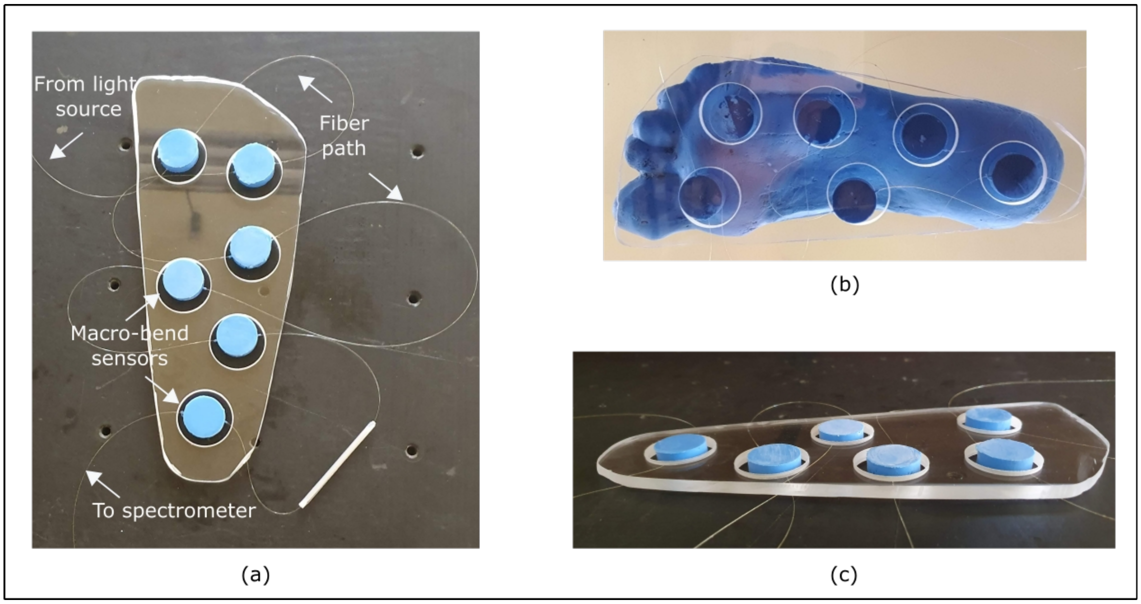

Fig. 1. Macro-bend sensing system used for foot type analysis in top view (a), bottom view (b) and side view (c).

For each foot type, 10 transmission spectra were collected under repeatability conditions. After recording a particular spectrum, the foot model under analysis was removed and afterwards repositioned on the plantar pressure measurement system. It is worth to highlight that in the methodology adopted for the tests, there was no concern in repositioning the foot model exactly at the same place for consecutive measurements. Therefore, the results obtained for each foot type are subject to differences of positioning that are expected in real applications. The 30 obtained spectra were then submitted to Principal Component Analysis (PCA) in order to evaluate the system ability to describe normal, flat and cavus feet characteristics. PCA is an efficient tool to cope with the large amount of information derived from obtained spectra. In addition to reduce data dimensionality, PCA algorithm is able to extract relevant features and combine them into new and few components simpler to compute and analytically tractable. The most relevant features or characteristics of the dataset are thus extracted and compose a new set of uncorrelated variables named principal components (PCs) [16]. These new components form a vector basis allowing clustering data that share similar information or characteristics, identifying regions for future classification.

Transmission spectra data obtained for the three foot types were normalized using the z-score technique and processed by the PCA, as described in a previous paper [15]. The use of two most relevant PCs allows data plotting in a two-dimensional graph in which the 3 foot types are visually identified.

3. Results and Discussion

The averaged transmission spectra of 10 measurements taken with each foot type are shown in Fig. 2(a). All spectra exhibit significant alterations with respect to the unperturbed system used as reference. From Fig. 2(a) it can also be inferred that these spectral modifications are strongly related to the shape of the foot. Fig. 2(b) shows two spectra (with offsets for better visualization) obtained during the tests with each foot type, providing a qualitative evaluation of the system repeatability.

Fig. 2 shows that dissimilar spectra are obtained for normal, cavus and flat feet indicating that the transmitted spectrum carries information that can be used for foot type recognition. After processed by the PCA, the raw dataset consisting of 30 transmission spectra was reduced into 2 main PCs. The points representing the samples in the new components, as well as the relevance of the first 10 principal components calculated for the system, can be seen in Fig. 3.

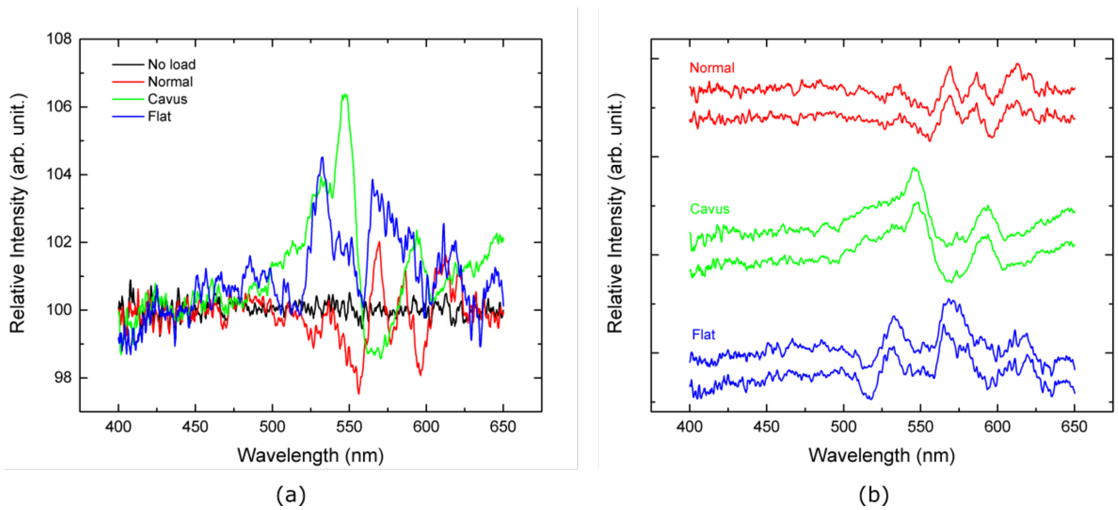

Fig. 2. Transmitted spectra: (a) for 3 foot types and (b) two representative spectra for each foot type.

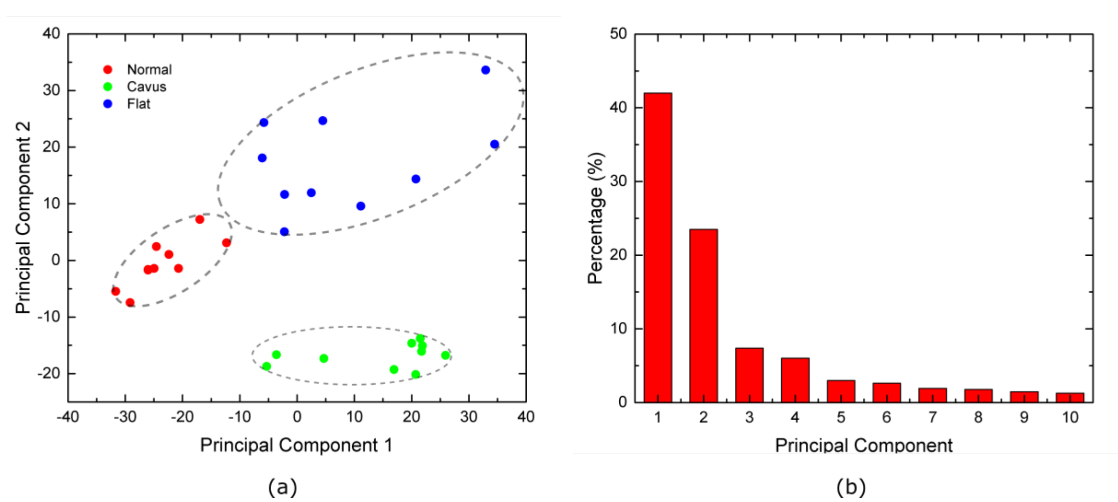

Fig. 3. Results of Principal Component Analysis: (a) points of the two first principal components for each foot type and (b) percentage of variance explained by each of the selected components.

As noted, the 10 footprint measurements associated with each foot type share well-delimited regions for the first two major components of the data set. This result demonstrates the sensor's capability of differentiate the foot types under consideration.

The quantitative characteristic that can be assigned to this dispersion is relative to the size of the hyperellipsoidally shaped cloud region representing each foot type. These regions correspond to the PCA scatter matrix derived from the sample covariance matrix by reducing its dimension through orthogonal projection. In fact, the eigenvectors of the scatter matrix are the axes of these ellipsoids. The biggest axes in Fig. 3(a) are nearly 24 for normal foot, 34 for cavus foot and 56 for flat foot, and the small ones are 11 for normal foot, 10 for cavus foot and 26 for flat foot. It is also worthwhile to mention that the first 2 principal components represent, respectively, 42.0%

and 23.5% of the information carried by the data. They refer to the PCA scatter matrix eigenvalues expressed as percentages, corresponding to the magnitude of the orthogonal eigenvectors and accounting for the data spread or scatter resulting in 65.5% of relevant information of the data set carried by principal components 1 and 2 together.

Finally, a foot type identification system can be easily carried out in four steps:

i) a person stands on the Macro-bend sensing system in Fig. 1;
ii) the signals are processed to generate the transmitted spectra data as in Fig. 2;
iii) a PCA algorithm extracts the two main principal components of the spectral data;
iv) the ellipsoidal region in Fig. 3 that will contain the pair of PCs determines the person's foot type.

4. Conclusion

Macro-bend sensing system has been built for foot type identification. The sensors are encapsulated in silicone elastomer and their distribution in the device are related to regions of interest for the foot type identification, resulting in distinct plantar pressure patterns for each foot type. Each foot type promotes spectral signals with proper features that are extracted by a PCA algorithm allowing the foot identification by a pattern recognition (PR) system.

The presented experimental results testify the PR system's ability to distinguish the 3 foot types defined in the literature (normal, cavus and flat) from the response of the multiplexed macro-bend sensors. Experiments are underway seeking for a better description of the ellipsoidal classification regions and also for mapping pressures (magnitude and location) exerted by the foot using regression methods and computational intelligence.

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