The design and development of a foot plantar pressure measurement based on the mechanically induced long period fiber grating

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Abstract. The aim of this study is to design and develop an alternative in-shoe foot plantar pressure measurement based on an optical fiber sensor. The foot plantar pressure distributions from human feet is considered to be important and essential information required by clinicians to plan a proper management on some foot problems of diabetic patients. Advantages of using the optical fiber include the immunity to electromagnetic interference, structural flexibility, light weight and low-cost assembly. The main component of the sensor is the long period fiber grating (LPFG) which is composed of a strand of single mode fiber (SMF, 9/125 μm) with a cut-off wavelength at 800 nm and plastic grooved plates with grating periods less than 1 mm. The gratings with different periods are placed at different regions in a foot platform whereby a patient's fore-foot, mid-foot and hind-foot are supported. The LPFG mechanically induced by the plantar pressure applied from each region can be observed from the resonance wavelength shift as a part of the transmission spectrum from the sensor. The data reveal both magnitude and position where the pressure is applied. Experimental results show that this system has a stable and reliable performance for measuring the foot plantar pressure distribution.

1. Introduction

Chronic diabetic patients are known to experience a loss of sensation in their feet. The problem is arisen due to the nerve damage and poor blood circulation. Patients who have the problem can have a risk of getting an excessive force exerting in particular point on their plantar feet. [1] This may lead to foot ulcers and result in lower extremity amputation. [2] Hence, a monitoring of foot plantar pressure distribution is necessary to chronic diabetic patients for planning a proper clinical management on this problem.

A variety of foot plantar pressure measurement systems have been developed in research laboratories and also available in the market. [3-4] The devices are classified into two main types; platform and in-sole systems. In platform systems, the pressure measurement sensor is embedded within a platform to monitor the foot plantar pressure. The device based on the platform system is suitable for being used in research laboratory whereas the device based on an in-shoe system can be utilized for monitoring the patient's foot plantar pressure distribution on real-life activities.

With the mentioned feature of the in-shoe system, small and compact parts for the sensing device assembly to monitor the foot plantar pressure are required. The mechanically induced long-period fiber grating (MLPFG) is a good candidate to be used in this work. This is because the use of the optical fiber give a number of advantage including the immunity to electromagnetic interference, structural flexibility, light weight and low-cost assembly. [5]

In this work, we have designed and developed a foot plantar pressure sensor distribution by using MLPFG as a sensing unit embedded in a foot platform. A prototype of foot plantar pressure measurement was presented. The transmission spectrum obtained from the MLPFG can be used to identify the position of perturbing pressure on a foot platform and determine the pressure magnitude. In addition, the response from the foot platform can clearly reflect particular foot types.

2. Method & Experimental Detail

2.1. A Mechanically induced long period fiber grating (MLPFG) sensor unit

The MLPFG is a single mode optical fiber(SMF) with a mechanically induced periodic structure. When a section of the SMF is pressed upon by a designed plate grating, the refractive index of the fiber is periodically modulated via the photoelastic effect. The MLPFG couples light from a fundamental guide mode into different forward propagation cladding modes which decay rapidly due to the radiation from scattering loss and bends in the fiber. A typical length for the long period grating is from 100 µm to 1mm. [6] In fig.1, a schematic of a MLPFG pressure sensing unit is shown. The unit is composed of 2 main parts, MLPFG part and protection part; i.e. cover and support plates. A SMF was placed between plastic support plate and plastic grooved plate having grating period less than 1 mm. The grating was simply created by 3D printer. To avoid an overloading on the SMF, a dummy optical fiber was placed next to the SMF.

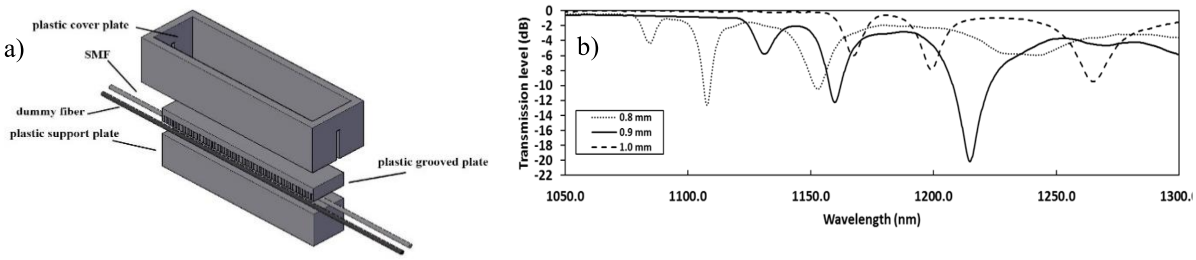

Figure 1, a) schematic of a MLPFG pressure sensing unit, b) attenuation spectra of a SMF with 0.8, 0.9 and 1.0 mm MLPFG under an applied force of magnitude 30.0 N.

Due to the energy coupling between core and cladding mode, the energy loss due to scattering give rise to the attenuation spectrum at certain wavelength following the phase matching condition.

$$\lambda_R = \left(n_{core} - n^i_{cladd}\right)\Lambda \tag{1}$$

where λ_R is attenuation wavelength called resonance wavelength, n_{core} and n^i_{cladd} are effective refractive indies of core, and the *i*th cladding within the optical fiber. Λ is the grating period. The operation principle of the proposed MLPFG structure pressure sensor is based on the wavelength shift of the attenuation bands of the MLPFG, when it is under the influence of the applied force.

2.2. A type of optical fiber

A strand of SMF with a cut-off wavelength of 800 nm was used in this study. Only one type of fiber coupling with three gratings having periods less than 1 mm can form three separate pressure sensing units on a foot platform. To facilitate the experiment procedure, FC connector were spliced to input and output of the SMF.

2.3. A Prototype of foot plantar pressure sensors

Three MLPFG pressure sensing units were placed at biomechanically significant positions; fore-foot, mid-foot and hind-foot [7] for monitoring foot plantar pressure distribution. The foot platform installed with the three sensing units is shown in fig.2a

a) b)

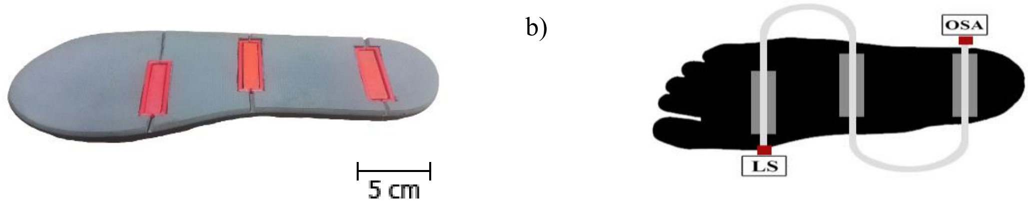

Figure 2, a) a prototype of in-sole MLPFG pressure sensor foot plate, b) schematic of an experimental setup of a MLPFG for monitoring foot plantar pressure; LS: light source, OSA: optical spectrum analyzer

The position of force exerted and the magnitude of force on the foot plantar platform sensed by the MLPFG pressure sensing units are observed through the attenuation wavelength shift. Three plastic grooved plates with different grating periods of 0.8, 0.9 and 1.0 mm were embedded at three positions; fore-foot, mid-foot, and hind-foot in the plantar foot platform. Fig. 2b illustrates a schematic of the experimental setup. Light from a broadband light source was launched into the optical fiber. When a foot subject perturbs on a MLPFG pressure sensor, the coupling between core and cladding modes occurs. This leads to an attenuation spectrum displayed on Optical Spectrum Analyzer(OSA) which can be used to determine both position and magnitude of the applied force on the foot plantar platform.

2.4. Data acquisition and analysis

The cladding modes corresponding to the matching condition have high attenuation clearly seen in the transmission spectrum. Fig. 1b shows that the period of the grating and/or the differential refractive index of the core and cladding result in a particular series of attenuation band centered at discrete resonance wavelength. In this study, the first band from attenuation series obtained from each sensing point is chosen to express the result of the perturbation due to the applied forces. The shift in the resonance wavelength from the change of the applied force can be detected and illustrated in a linear correlation between the wavelength shift and the applied force in Fig. 3a.

2.5. A dummy fiber

The function of a dummy fiber can in fig.1 is to share the load-exerting force with the SMF in each sensing unit. Without an appropriate number of the dummy fibers, the force simultaneously applied on the concatenated sensing units results in obscurity of individual transmission spectra and inability to interpret the experimental results. The number of dummy fiber were optimized so as to maintain the correct response from individual sensing point. Short strand fibers of 6, 5 and 1 were introduced to the fore-foot, mid- feet and hind-foot areas, respectively.

3. Results and Discussions

Fig. 3 shows a linear response of resonance wavelength due to the standard force exerting on a separate sensor without a dummy fiber. In order to achieve the linear response, the applied force was found to be in the range of 10.0-70.0 N. Although the magnitude of the force applied by the real plantar foot is greater than 70.0 N, an individual sensing unit can still give a proper response with the assistance of the dummy fiber mentioned in the previous section. The feature can extend the range of force limit to 70.0-490.0 N at fore-foot, 60.0-420.0 N at mid-foot and 20.0-140.0 N at hind-foot region. The range extension is suitable for the measurement of the foot plantar pressure in a real foot.

In order to classify types of human feet; low arch or flat feet, medium arch, and high arch, the average force measured by sensing units embedded in the foot platform was considered. In fig. 3b, the force exerting on each sensing unit from arch foot and flat foot of participants are shown. In the figure, the solid symbols are the average force values exerting on sensing units of three measurements and the lines are the maximum and minimum ranges of measurement value. In case of arch foot, sensing units at fore-foot and hind-foot can measure a large average force value than the sensor at mid-foot does. In flat feet, a sensing unit at mid-foot can measure a different force exerting on the sensor from the one obtained from the arch foot.

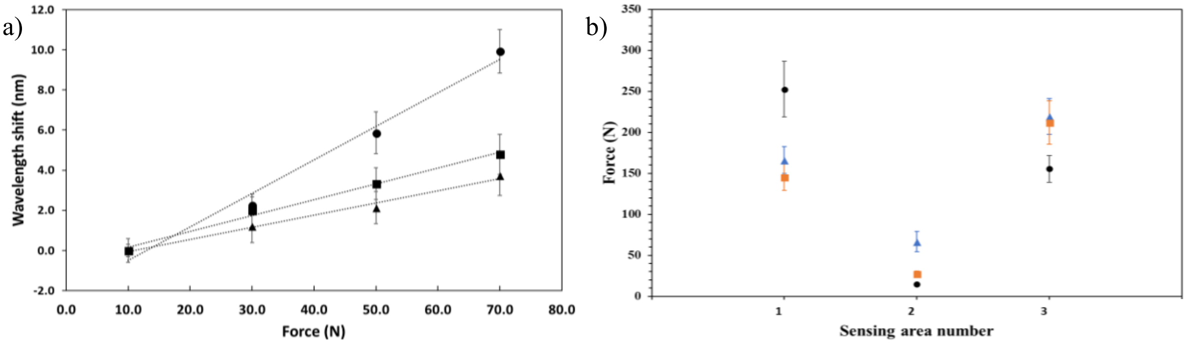

Figure 3. a) A linear response of resonance wavelength shift due to standard force perturbation on a separate sensor without a dummy fiber. ■, ▲ and ● represent data obtained from using grating periods of 0.8, 0.9 and 1.0 mm respectively. b) The response from the foot platform due to the average force exerting on each sensing area. Sensing numbers of 1, 2, and 3 represent sensing units embedded at fore-foot, mid-foot, and hind-foot areas respectively, ▲, ■ and ● shows the average force values due to force applied from flat-arch, medium-arch and high-arch feet respectively.

These features correspond to the natural characteristic of feet type in which the most force exerting on fore-foot and hind-foot are from the arch foot type and forces exerting over a fore-foot, mid-foot, and hind-foot are from the flat foot type. An average force exerting on sensing unit having slightly change is caused by the inconsistent standing position of the participant's foot.

4. Conclusions

In this work, a mechanically induced long period fiber grating (MLPFG) was designed, developed and implemented in an in-shoe foot plantar pressure distribution sensor. A MLPFG pressure sensors with grating period 0.9, 1.0 and 0.8 mm were placed at three regions; fore-foot, mid-foot and hind-foot respectively. The prototype of the foot platform embedded with a combination of MLPFG pressure sensors were also fabricated in this work. In addition, the human foot types feet were investigated and clearly identified.

5. Acknowledgement

This research work was financially supported by the research development grant from the faculty of science, Mahidol university.

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