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Design and development of Fiber Bragg Grating sensing plate for plantar strain measurement and postural stability analysis

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ABSTRACT

This paper describes an *ab initio* design and development of a novel Fiber Bragg Grating (FBG) sensor based strain sensing plate for the measurement of plantar strain distribution in human foot. The primary aim of this work is to study the feasibility of usage of FBG sensors in the measurement of plantar strain in the foot; in particular, to spatially resolve the strain distribution in the foot at different regions such as fore-foot, mid-foot and hind-foot. This study also provides a method to quantify and compare relative postural stability of different subjects under test; in addition, traditional accelerometers have been used to record the movements of center of gravity (second lumbar vertebra) of the subject and the results obtained have been compared against the outcome of the postural stability studies undertaken using the developed FBG plantar strain sensing plate.

1. Introduction

The need for plantar strain measurement has gained immense interest among researchers and clinicians over past few decades [1–4]. The singularly most interesting problem that brought about the advancement in this field is the management of diabetic foot [5–7]. In the recent times, the number of people suffering from neuropathic or vascular ulceration of the foot has increased; a combination of peripheral neuropathy and vascular inefficiency pre-disposes the diabetic foot to physical trauma and ulceration; subsequent infections and possible onset of gangrene may lead to leg amputations [8–13]. Furthermore, most peripheral neuropathies damage nerves of the limbs, especially the foot, on both sides, thus leading to balance impairment [14–17]. Hence, there is a pressing need to have an objective assessment of plantar strain distribution to identify patients with a risk of plantar ulceration and also to understand the underlying mechanism.

The measurement of dynamic strains beneath the plantar aspect of the foot provides a quantitative means of assessing the plantar weight bearing patterns reflective of the biomechanical transfer of load through the structure of the foot. In literature, a multitude of solutions have been suggested to assess the distribution of plantar strains [18–20]. These solutions, suggest the use of different sensing methodologies for the study of plantar strain distribution as well as the postural stability analysis, such as capacitive, resistive, and piezo-electric [3,4,7,19,21–24]. Most of these sensors are from electrical domain which may be limited by accuracy, sensitivity, reliability, strain sensing range, sensor size, etc. In addition, the electrical sensors are prone to interference from electromagnetic

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fields which constraint their usage in close vicinity for biomechanical applications.

The current work focuses on the novel applicability of Fiber Bragg Grating (FBG) sensors which addresses most of the above highlighted problems in plantar strain measurement and postural stability analysis [25]. The use of FBG sensors is growing in importance, both for intermittent and for continuous monitoring of variety of critical engineering parameters in diverse fields [26–29]. These sensors can detect many different parameters including strain, temperature, pressure, vibration, refractive index of the surrounding materials, etc. [30,31], even in high magnetic and electric field environments. Therefore, they can serve in diagnostic purposes and in different areas of healthcare such as biomechanics, cardiology, gynaecology, and immuno-sensing [32].

The present work also investigates, quantifies, and compares the relative postural stability of tested subjects from the recorded strain history of the FBG sensors with calibrated accelerometers [33–36] which records the Center of Gravity (CG) movements. By calculating the mean amplitude and variance of the measured FBG sensor data, the results pertaining to plantar strain distribution and postural stability for various subjects are evaluated respectively.

2. Experimental details

2.1. Subjects

10 healthy subjects (5 female and 5 male; mean ± SD Age = 26 ± 3 years), free from any musculo-skeletal or neurological disorders, volunteered for this study. Subjects with comparable foot size to suit the developed sensing plate have been chosen. These subjects were advised not to consume alcohol or any sort of medication, 24 h prior to the commencement of the experiment. The subjects were also instructed about the experiment and each subject was given a trial run before the readings were taken.

2.2. FBG sensor layout

The schematic of the plantar strain sensing plate comprising of FBG sensors bonded between two perspex sheets is shown in Fig. 1. Individual foot sensing plates for both feet are firmly secured on a flat wooden plank. The upper perspex sheet of the sensing plate is divided into three separate segments, each constituting one FBG sensor. In order to carry out the feasibility study, three sensors for each foot at biomechanically significant positions i.e., the forefoot, mid-foot and hind-foot are chosen to measure the plantar strains [7]. Independent fibers (channel 1 and channel 2), each carrying three FBGs of varying Bragg wavelengths have been used for each of the foot. A small protrusion is provided at the end of the perspex sheet which acts as a reference or datum for the subjects to appropriately position their feet on the sensing plate.

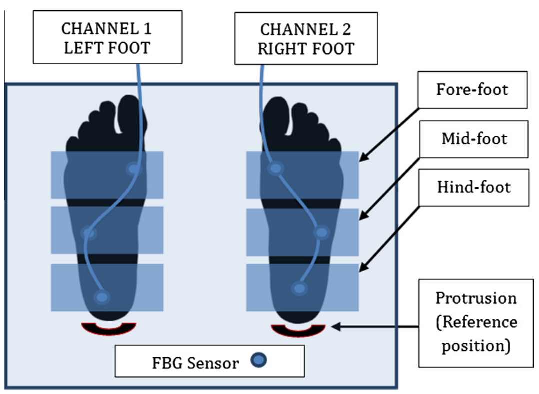

Fig. 1. Schematic design of the plantar strain sensing plate.

2.3. Procedure

The experiment is conducted in an isolated room in order to eliminate any possibility of external vibrations interfering with the measured plantar strain data. The subjects are suggested to comfortably stand on the sensing plate with the heels touching the small protrusions, provided for each foot to acts as a reference. An Accelerometer is mounted at the CG of the subject's body i.e., second lumbar vertebra [37]. All the ten volunteered subjects are instructed individually to stand on the sensing plate continuously for a period of 30 s with an interim gap of 5 min to avoid any possible error due to muscle fatigue.

3. Sensor instrumentation details

The sensor elements used in the present study are FBG sensors; FBG is a periodic or quasi periodic modulation of the refractive index of the core of the photosensitive, germania doped, silica fiber achieved by exposing it to an intensity modulated UV light [25]. Over the years, there have been several techniques developed to inscribe the gratings in an optical fiber [38,39]. The present study uses the phase mask inscription technique which has evolved itself as the most effective method to fabricate Bragg gratings using the UV radiation from a 248 nm KrF laser [40].

For quantifying the relative postural stability of the subjects under test, the real time strain recorded from FBG sensors are compared against a calibrated tri-axial accelerometer (ADXL326) [36,41] of 60 mV/g sensitivity which records the movements at CG of the subjects. The axes system adopted in the present study for the accelerometer is shown in Fig. 2. All measurements are obtained with respect to the accelerometer's fixed axes system. The accelerometer provides the accelerations along X, Y, and Z axes.

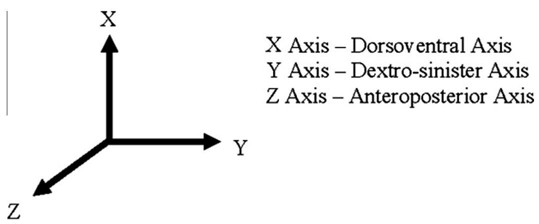

Fig. 2. Axes system used for accelerometer measurements.

4. Data acquisition and analysis

In order to facilitate easy post-processing of the data, FBG sensors and accelerometers have been configured to acquire data at a sampling rate of 50 Hz. Data from plantar strain sensing plate is recorded simultaneously from all the 6 FBG sensors corresponding to both the feet, using a commercial FBG sensor interrogation system (Micron Optics SM-130). Since the obtained data from the FBG interrogator is in the form of reflected Bragg wavelength, a predetermined wavelength to strain conversion factor of 1.22 pm/με is used to obtain the corresponding strains from each of the sensors.

As ten subjects are involved in the present study, a box-plot analysis is used which summarizes all the data measured on an interval scale, helping to compare different sets of measured data values. This type of analysis represents the strain distribution, mean, median, and percentile ranges for better analysis and comparison of the measured plantar strain data among the volunteered subjects. In the data of 30 s, the initial 5 s and final 5 s are neglected to avoid possible errors due to ingress and egress of the subjects on the sensing plate. Only the data from interim 20 s duration are averaged to obtain a single strain value for a single FBG sensor for each of the trials. A similar procedure has been carried out for all the ten subjects. The resulting averaged values are used in the box-plot analysis.

5. Results and discussions

In order to obtain the plantar strain distribution pattern, the magnitude of the averaged strains at different portions of the foot is used whereas the variance of strain with respect to time is used for postural stability analysis of the subjects.

5.1. Plantar strain measurement

Fig. 3 shows the statistical analysis of three independent trials conducted on two typical subjects. The average plantar strain value for the intermediate 20 s out of the 30 s test time of the subject on the sensing plate has been obtained for each of the conducted trials for all the ten subjects. Based on the spread in standard deviation values of any of the sensor position in Fig. 3, it can be said that the three trials of plantar strain distribution corresponding to an individual is consistent.

In case of subject 1, it can be seen that the strain is greater in the locations 'RIGHT FRONT' and 'LEFT FRONT' compared to the rest of the sensor positions. Similarly, for the subject 2, the sensors positioned at the location 'RIGHT HIND' and 'LEFT HIND' experiences higher strains compared to other locations of the foot. This information can serve as a yardstick to an ergonomics specialist or podiatrician to design customized insoles for distributing excess strains applied on specific parts of the foot uniformly to rest of the locations of the foot [9,10,12,42,43]. Similar investigations have been carried out for rest of the participants.

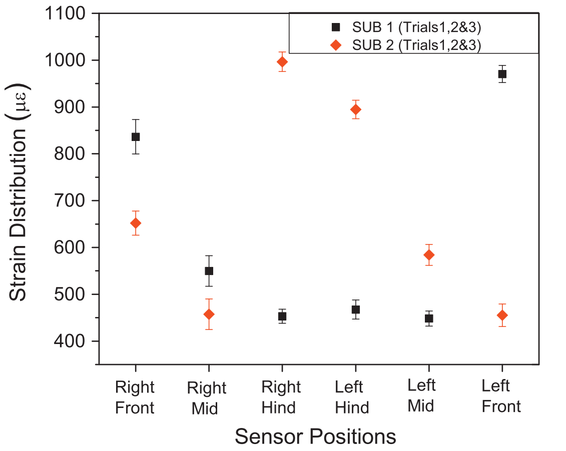

Fig. 3. Statistical analysis of three trials measuring plantar strains at different regions of the foot for two typical subjects.

5.2. Subjective analysis and comparison of postural stability

Postural stability of a person can be subjectively studied with the help of the developed plantar strain sensing plate. Postural stability is an index proportional to the variations in the plantar strain values with respect to time. For validating the results of the FBG plantar strain sensing plate, an accelerometer is mounted on the subjects at the center of gravity of the body (second lumbar vertebra). It has been shown by Hasan et al. that greater the Center of Pressure (COP) excursions, greater is the imbalance [44]. Also, lesser the variation of CG movements, greater is one's stability [45,46].

Fig. 4 shows the box-plot analysis of variance of the summated plantar strains sensed at different locations of the feet for each subject. Similarly, Fig. 5 corresponds to the box-plot of movements recorded by the accelerometer positioned at CG. Observing Figs. 4 and 5, it can be inferred that among all the tested subjects, subjects 5 and 9 show a larger variation in mean compared to the rest of the volunteered subjects implying lesser stability; whereas subjects 2 and 10 exhibit the least variation in mean among the

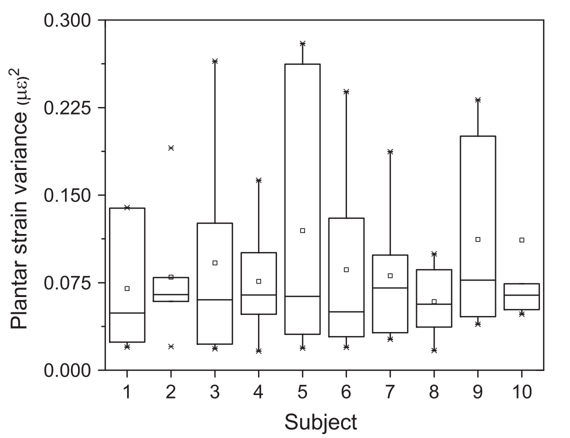

Fig. 4. Box plot of plantar strain variance for all subjects.

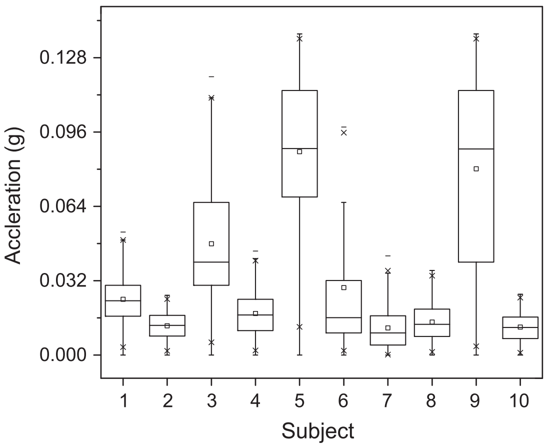

Fig. 5. Box plot of acceleration at CG for all subjects.

tested 10 subjects, showing better stability. From the plots of both FBG plantar strain sensing plate and accelerometer (Figs. 4 and 5), the trend in postural stability of all the subjects involved have been found to be in good agreement. This match in trend between the obtained results confirms the reliability and consistency of the developed FBG plantar strain sensing plate.

6. Conclusions

This paper brings out the utility of non-electrical, non-invasive and easy to use FBG sensors in the development of plantar strain measurement plate for both plantar strain measurement and postural stability analysis. The magnitudes of the plantar strains sensed by FBG sensors and the pattern of strain distribution obtained can be used to identify the areas experiencing excess strain compared to other locations of the foot. This information can serve as a yardstick to an ergonomics specialist or a podiatrician to design customized insoles for distributing excess strain applied on specific parts of the foot uniformly to rest of the locations of the feet. The variation of the strain values have also been compared against a commercial accelerometer based CG variation results for postural stability analysis.

As the FBG sensor is small in size, capable of multiplexing, free from electromagnetic interference and needs no energizing current to activate the sensor, the demonstrated plantar strain measurement plate has great potential for use in biomechanical applications involving human trials.

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