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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.

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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 \pm 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

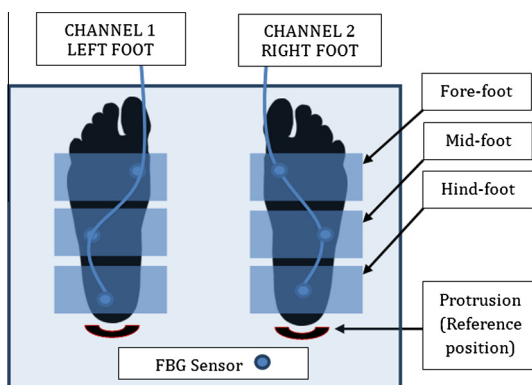


Fig. 1. Schematic design of the plantar strain sensing plate.

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 fore-foot, 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.

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.

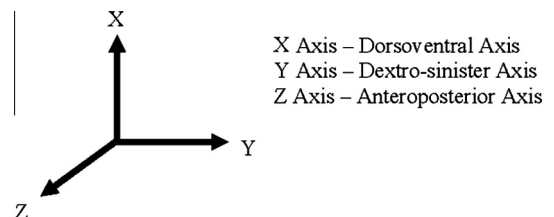


Fig. 2. Axes system used for accelerometer measurements.

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