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Design and Development of Optical Sensor Based Ground Reaction Force Measurement Platform for GAIT and Geriatric Studies

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***Abstract*—**This paper describes an ab-initio design, development and calibration results of an Optical Sensor Ground Reaction Force Measurement Platform (OSGRFP) for gait and geriatric studies. The developed system employs an array of FBG sensors to measure the respective ground reaction forces from all three axes (X, Y and Z), which are perpendicular to each other. The novelty of this work is two folded. One is in its uniqueness to resolve the tri axial resultant forces during the stance in to the respective pure axis loads and the other is the applicability of inherently advantageous FBG sensors which are most suitable for biomechanical instrumentation. To validate the response of the FBG sensors installed in OSGRFP and to measure the cross sensitivity of the force applied in other directions, load sensors with indicators are used. Further in this work, relevant mathematical formulations are presented for extracting respective ground reaction forces from wavelength shifts/strain of FBG sensors on the OSGRFP. The result of this device has implications in understanding the foot function, identifying issues in gait cycle and measuring discrepancies between left and right foot. The device also provides a method to quantify and compare relative postural stability of different subjects under test, which has implications in post-surgical rehabilitation, geriatrics and optimizing training protocols for sports personnel.

***Keywords*—**Balance, stability, Gait analysis, FBG applications, optical sensor ground reaction force platform.

I. Introduction

HUMAN foot will be subjected to ground reaction forces in every walk of life, like normal stance to extensive physical exercises. These forces have been studied for decades to understand force functions, to reduce the related injuries and to increase comfort for better life style.

In literature, various solutions have been proposed to assess the distribution of plantar strains and to measure ground reaction forces [1]-[6]. These suggested solutions use diverse sensing methodologies such as capacitive, resistive, piezo-electric, etc. [7]-[12]. Most of these sensors are from electrical domain, which may be limited by accuracy, sensitivity, reliability, force sensing range, sensor size, etc. In addition, the electrical sensors are prone to interference from electromagnetic fields which constraints their usage in biomechanical applications.

The need for Ground Reaction Force (GRF) measurement has gained immense interest among researchers and clinicians over past few decades [13], [14]. The singularly most interesting problem that brought about the advancement in this field is the management of diabetic foot [15], [16].

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 insufficiency pre-disposes the diabetic foot to physical trauma and ulceration; subsequent infection and possibly the onset of gangrene leading to the necessity for leg amputations [17]-[22]. Furthermore, most peripheral neuropathies, damage nerves of the limbs, especially the foot, on both sides and thus leading to balance impairment, which can be obtained from measurement of GRFs [23]-[26]. Hence, there is a pressing need to have an objective assessment of GRFs measurement devices to critically identify patients with a risk of plantar ulceration and also to analyze the underlying force acting mechanism.

The use of FBG sensors are growing in importance, both for intermittent and for continuous monitoring of variety of critical engineering parameters in diverse fields [27]-[30]. These sensors can detect a variety of parameters including strain, temperature, pressure, vibration, and refractive index of the surrounding material, even in high magnetic and electric field environments [31], [32]. Therefore, they can serve in diagnostic purposes and in different areas of healthcare such as biomechanics, cardiology, gynaecology, and immuno-sensing [33]. The use of Fiber Braggs Grating (FBG) as sensors in the development for measurement of ground reaction forces was well explored in literature [34].

Present work details about the design and development of an Optical Sensor Ground Reaction Force Measurement Platform (OSGRFP) using inherently safe FBG sensors, which has critical implications in many fields of the biomechanical engineering.

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II. Design Details of OSGRFP

The unique mechanical design of this work enables the explicit measurement X, Y and Z-axis forces from the total resultant force.

The OSGRFP is supported from the bottom by four legs on the ground and has another two legs, each on the other two perpendicular directions. The side legs are attached to lateral supports using the special type of universal joints, which enable to produce the motion only in the direction of loading and restrict in the other directions. The universal joints (2 in X axis, 2 in Y axis) provide the free motion in only one axis and constrain motion are in other two axes facilitating the pure axis force measurement whereas the 4 ball joints provided at the bottom of the plate offers the point contact with the ground.

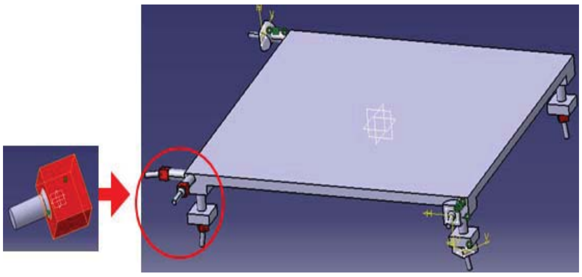

Fig. 1 Schematic picture of the ground reaction force measurement platform with ball joint supports

The three dimensional diagram of the complete ground reaction force measurement platform with joints and supports for explicit pure axis force measurement is outlined in Fig. 1.

III. Formulations for Extraction of Force from Measured Strain

The fundamental change in the FBG sensor for the applied load is in the physical change in length or dimensions. This physical deformation will be indicated in terms of change in the Bragg wavelength of the FBG sensor which can be converted to respective strain from the simple formulations explained both in theoretical and empirical form in the literature [31]. However, calculation of force from the strain observed by the FBG sensor which is of the parameter of interest in GRFP is explained in the subsequent section.

Consider the following nomenclatures for various parameters like strain (ε) and Force (F) in different axes, Young's modulus (Y), Stress (σ) and Area (A).

For the two FBG sensors on OSGRFP in X axis, let ε_{x1} - Strain obtained from FBG_{X1} of X axis, ε_{x2} -Strain obtained from FBG_{X2} of X axis, ε_x –Total Strain obtained from X axis sensors. Similarly, for Y axis, let ε_{y1} - Strain obtained from FBG_{Y1} of Y axis, ε_{y2} - Strain obtained from FBG_{Y2} of Y axis, ε_y – Total strain obtained from Y axis sensors.

Since there are four FBG sensors each on the four different legs of the OSGRFP, following nomenclature is considered; ε_{z1} - Strain obtained from FBG_{Z1} of Z axis sensor, ε_{z2} - Strain obtained from FBG_{Z2} of Z axis sensor, ε_{z3} - Strain obtained from FBG_{Z3} of Z axis sensor, ε_{z4} - Strain obtained from FBG_{Z4} of Z axis sensor, ε_z –Total strain obtained from X axis sensors.

For Calculation of Force (F) from the obtained strain readings of FBGs mounted on OSGRFP, following fundamental equations can be used.

Force = Young's Modulus * Area/ Strain,

$$F = Y * A / \varepsilon \tag{1}$$

For calculation of Forces in the respective, X, Y and Z axes, following formulation can be used.

$$F_x = \text{Medio-lateral force} = F_{x1}+F_{x2} \tag{2}$$

$$F_y = \text{Anterior-posterior force} = F_{y1}+F_{y2} \tag{3}$$

$$F_z = \text{Vertical force} = F_{z1}+F_{z2}+F_{z3}+F_{z4} \tag{4}$$

IV. Sensor Instrumentation Details

An array of FBG sensors of varying Bragg wavelength are fabricated in a single fiber enabling multi point sensing using a single fiber [32]. Three independent fibers carrying a total of 8 FBG sensors (2 FBGs in X axis: FBG_{X1} and FBG_{X2}, 2 FBGs in Y axis: FBG_{Y1} and FBG_{Y2} and 4 FBGs in Z axis: FBG_{Z1}, FBG_{Z2}, FBG_{Z3} and FBG_{Z4}) are used for sensing strain in all three axes of OSGRFP. An interrogation system (SM 130-700) from Micron Optics Inc. is used for real-time recording of the centre wavelengths of all the FBG sensors instrumented in the experiment. Fig. 2 shows the picture of the FBG sensors instrumented on the developed OSGRFP.

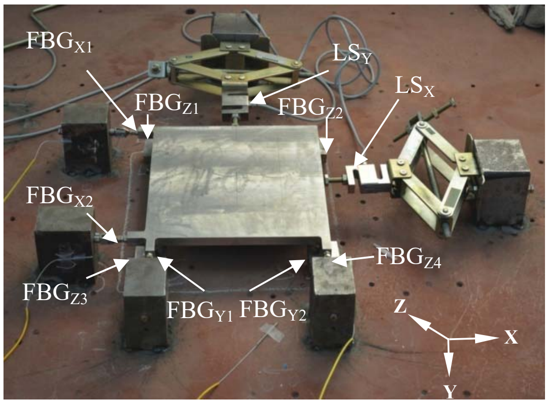

Fig. 2 Photograph of the FBG sensor instrumented on OSGRFP

Several solid load blocks are used to build and firmly hold OSGRFP, avoiding any possible movement/slipping while loading, which may add errors in to the measurement of pure axis force. Fig. 2 also shows two load sensors (LS_X, LS_Y) coupled with scissors type mechanical jack on either direction (X and Y direction). These load sensors are used for calibration of the FBG sensor and also to validate the cross-force sensitivity of the OSGRFP.

V. Calibration Procedure

Before inducting the developed OSGRFP for clinical trials, systematic calibration trials have been conducted to ensure that the design parameters are satisfactorily met though evaluation of cross-force sensitivity. For pure axis loading in X and Y directions, two scissors type mechanical jack as shown in Fig. 2 are used. These two jacks are manually turned/tightened to load OSGRFP in X and Y axis, whereas for Z axis loading, dead weights are piled up at the center of the platform as shown in Fig. 3. Fig. 3 also shows the dead weights used for loading along the Z axis, the load cell indicator, FBG interrogation system and other necessary accessories of the experimental setup. An incremental load of 10kN was applied till the load indicator reads 140kN in both X and Y directions. To monitor the magnitude of load applied from the mechanical jacks of X and Y axis, two commercial load cells along with load cell indicator are used.

Fig. 3 Experimental setup for calibration of Z axis sensors

VI. Experimental Results

This section of the results details about the three calibrating test cases where, the response of FBGs and load cells were tested to validate the design of OSGRPF. Fig. 4 shows the responses of all the sensors instrumented on OSGRPF where the mechanical jack positioned along X axis is tightened to increase the long along X axis by an amount to 10 kN till a maximum load of 140 kN. In Fig. 4, real-time is plotted in X axis whereas deferent units sensors (Strain for FBGs and Load for Load cells) are plotted against Y axis. It can be observed that the FBG sensor has recorded a maximum strain of around 20με which is well within the sensing limits of the FBG sensors. Since the loading is in the direction of the X axis, it is expected that the FBG and load cell in X axis receives the full load applied which is evident from the results. However, it can be noted that the response of other sensors in Y and Z direction are negligible depicting the zero cross-force sensitiveness. Similarly, it can be seen from Fig. 5 where the load applied though the mechanical jack of Y axis, the FBG and Load cell along the Y axis have reacted not allowing the other sensors (X and Z axis) to absorb the load. This will also quantify the zero cross-force sensitivity along Y axis. From Fig. 5, it is evident that the load sensor of the Y axis follows the shape of a staircase response of the FBG sensor positioned in Y axis with each step corresponding to the number of turns given by the mechanical jack in the Y axis.

During the calibration and testing of the sensors along Z direction as expected, a dead weight of 800 N was piled momentarily at the center of the plate. The response of a typical FBG sensor positioned along the loading axis (Z axis) is plotted in real time with comparison to the sensors of other directions which can be seen from Fig. 6. It can be seen from the Fig. 6, that the sensor along Z direction reacts to this loading where responses of the sensors along the other directions are negligible proving the zero cross-force sensitivity along the Z direction.

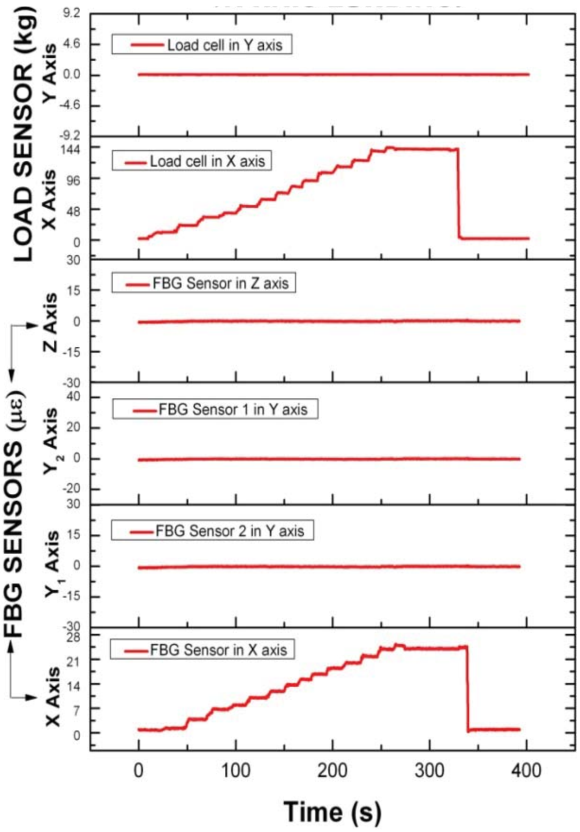

Fig. 4 Calibration results with X axis loading

VII. Conclusion

This study details the design, development and calibration results of an Optical Sensor Ground Reaction Force Measurement Platform (OSGRFP) based on FBG sensors which has implications in the area of gait and geriatrics. The mandatory design goal of realizing zero cross-force sensitiveness in all the three loading axes was achieved through unique design of the OSGRFP and a simple custom made calibration setup. Further in this work, necessary mathematical formulations are presented for extracting respective ground reaction forces from wavelength shifts/strain recorded from FBG sensors on the OSGRFP. The result of this study has implications in various field of biomechanical engineering for understanding critical behavior of human body under various loading conditions.

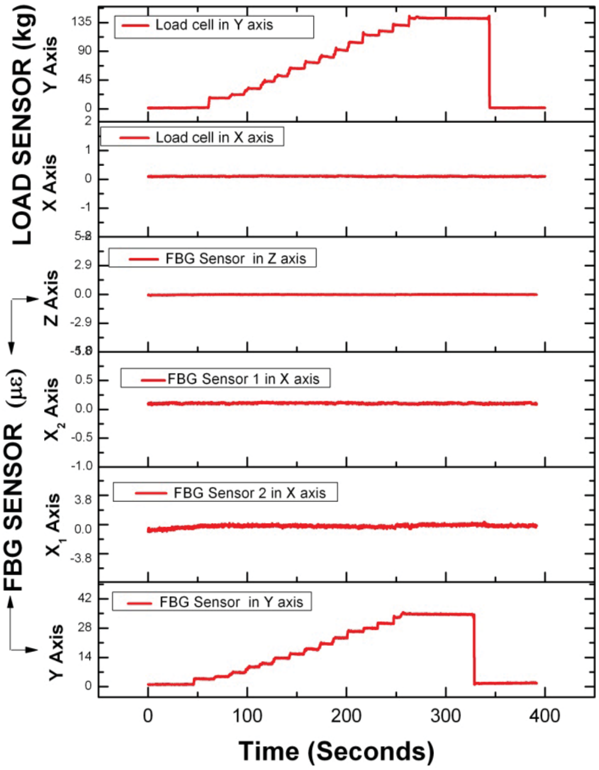

Fig. 5 Calibration results with Y axis loading

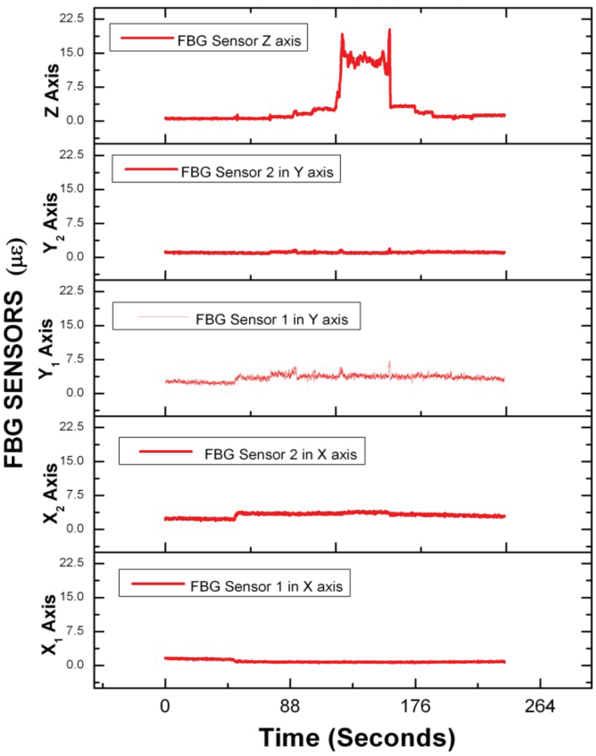

Fig. 6 Calibration results with Z axis loading

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