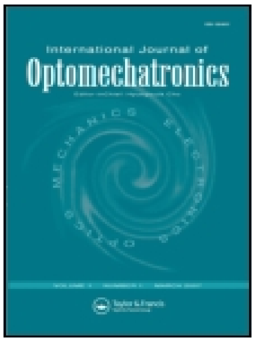

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A NOVEL FIBER BRAGG GRATING BASED SENSING METHODOLOGY FOR DIRECT MEASUREMENT OF SURFACE STRAIN ON BODY MUSCLES DURING PHYSICAL EXERCISES

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The present work proposes a new sensing methodology, which uses Fiber Bragg Gratings (FBGs) to measure in vivo the surface strain and strain rate on calf muscles while performing certain exercises. Two simple exercises, namely ankle dorsi-flexion and ankle plantar-flexion, have been considered and the strain induced on the medial head of the gastrocnemius muscle while performing these exercises has been monitored. The real time strain generated has been recorded and the results are compared with those obtained using a commercial Color Doppler Ultrasound (CDU) system. It is found that the proposed sensing methodology is promising for surface strain measurements in biomechanical applications.

Keywords: Fiber Bragg grating sensor, leg exercise evaluation, optical sensing, skin surface strain measurement

1. INTRODUCTION

Measurement of strain/deformation on body surface has gained importance and has become an area of intense research since few decades (Wan and Barbenel 1982; Wan 1994; Marcellier et al. 2001). There have been several studies recently, both in vivo and in vitro, on the surface strain on both living and dead subjects (Sivamani et al. 2003; Mahmud et al. 2010; Kwiatkowska et al. 2009). The surface strain measurement methodologies generally vary from techniques like finite element method, digital image correlation method (Peters et al. 1983; Evans and Holt 2009),

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optical analysis method, etc., employing specialized devices like 3-D motion capture system, Micro-Tribometer and echo-rheometer (Diridolou et al. 1998).

The simulation and modeling of strain invariably involve some assumptions which have an impact on the accuracy of measurements (Law & Kelton 2000). The non contact type measurements such as 3-D motion capture method, Micro-Tribometry and echo-rheometry demand that the field of measurements be in line-of-sight which restricts the usage of these techniques for the static experiments. In order to address the above issues, a surface mounted sensor suitable for biomechanical applications is imperative.

A human muscle strain injury can be simulated in the laboratory (Wan and Barbenel 1982; Wan 1994) by the over-stretch of an isolated muscle. A muscular injury generally occurs at the musculo-tendinous junction (as seen in human in-vivo strains) although it can sometimes occur in the muscle belly (Marcellier et al. 2001). Most of the laboratory simulated muscle injury experiments have revealed that the strain is the property that correlates most with the muscle damage. Strain has been shown to have a greater correlation with muscle damage than other parameters such as muscle force (Wan and Barbenel 1982), velocity (Sivamani et al. 2003), strain rate (Mahmud et al. 2010) and contraction status of the muscle (Kwiatkowska et al. 2009).

The highest strain a muscle can withstand is that from being fully shortened to fully lengthened, for example during a slow muscle stretching exercise. It is very uncommon that a slow stretch or low strain rate ever results in a muscle strain injury. As a muscle is stretched towards its maximum length, it passively resists the stretch (Birschoff et al. 2000). In activities that typically cause muscle strain injuries (e.g., hamstring strains during sprinting), even if the maximal range of motion of muscle groups (and hence maximal strain) is not reached, a muscle strain injury can result. This implies that in addition to strain, velocity, strain rate or contraction status of the muscle may also be relevant in creating a muscle strain injury. Of these, measurement of muscle strain and strain rate during various phases of activity or exercise is crucial.

This article proposes a new sensing methodology for measuring surface strains on calf muscles using FBG sensors which do not require electrical excitation and are also insensitive to electromagnetic interference (Othonos 1997; Perry 1984). For illustrating the usefulness of the proposed methodology, two exercises, namely ankle dorsi-flexion and ankle plantar flexion have been chosen; these leg exercises are one among the most common and effective way for analysis of muscles of the legs and knees (Kellis et al. 2005; Biette et al. 2004; Sibel et al. 2008).

The results obtained have been validated by Color Doppler Ultrasound (CDU) method. During validation, the FBG sensor is mounted on the medial head of the gastrocnemius calf muscle while performing these exercises and the real time strain data obtained is compared against the blood velocity change in the femoral vein of the thigh obtained from the CDU technique.

2. FBG SENSORS—WORKING PRINCIPLE

FBGs are sensor elements fabricated directly in the core of a photosensitive single mode optical fiber. An intensity modulated UV beam is used to induce periodic changes in the refractive index in the core of the fiber (Fujii et al. 1978), by exposing it to the laser beam through a phase mask which creates an interference pattern in the core of the fiber (Fujii et al. 1978; Hill et al. 1997; Albert et al. 1993).

When light from a broad band source is launched into the fiber with a Bragg grating inscribed in it, a certain wavelength (λ_B) is reflected back and the rest are transmitted through. The wavelength of the reflected light (λ_B) depends on the spacing between periodic variation of refractive index (Λ) and the effective refractive index of the core n_{eff} and is given by

$$\lambda_B = 2\, n_{eff} \Lambda. \quad (1)$$

The spacing of the periodic variation of the refractive index, changes with any external strain on the fiber (Udd 1991). Also, due to the strain-optic effect, the effective refractive index will be changed. The Bragg wavelength shifts due to external axial strain on the fiber, which can be expressed as

$$\frac{\Delta\lambda_B}{\lambda_B} = K\varepsilon. \quad (2)$$

Here, K is a constant and ε is the applied strain on the sensor. FBG sensor also responds to changes in the temperature surrounding it, which can be neglected if the experiment is carried out under controlled temperature conditions or properly compensated (Cavaleiro et al. 1991; Rahman et al. 2010).

The FBG sensors used in the present set of experiment have been fabricated in the laboratory with a Krypton Fluoride Excimer laser at 248 nm using the phase mask technique (Gupta et al. 1996). Bare FBG sensors of 90% reflectivity at 1550 nm range with a strain coefficient of 1.22 pm/$\mu\varepsilon$ have been used.

3. EXPERIMENTAL PROCEDURE

i. **Ankle Dorsi-Flexion and Ankle Plantar-Flexion Exercises**
Since the zone of interest is the medial head of the gastrocnemius, simple but effective leg exercises, namely ankle dorsi-flexion and ankle plantar-flexion, are chosen (Poulis and Soames 2003; Applegate et al. 2000).
Figure 1 shows the pictorial representation of the human foot in normal posture, dorsiflexion and plantarflexion posture. Figure 1*a* shows the subject sitting on a chair comfortably resting his foot on the floor. Figure 1*b* shows the dorsiflexion of the foot which is the movement that flexes the foot or the toe in an upward direction; this decreases the angle between the dorsum (superior surface) of the foot and the leg, so that the toe is brought closer to the shin. Figure 1*c* shows the plantarflexion posture, which is the flexion of the foot downwards towards the sole increasing the angle between the dorsum (superior surface) of the foot and the leg, so that the toe is pushed away from the shin.

ii. **Subjects**
Ten healthy subjects willingly volunteered for this work. Subjects of both sexes (five females and five males), aged between 24–30 years (mean age: 27 years) and of varying Body Mass Index (mean BMI: 21) participated in the experiment. The subjects have been examined by a standard medical practitioner the day prior to the experiment and found to be in good health condition. Also, the

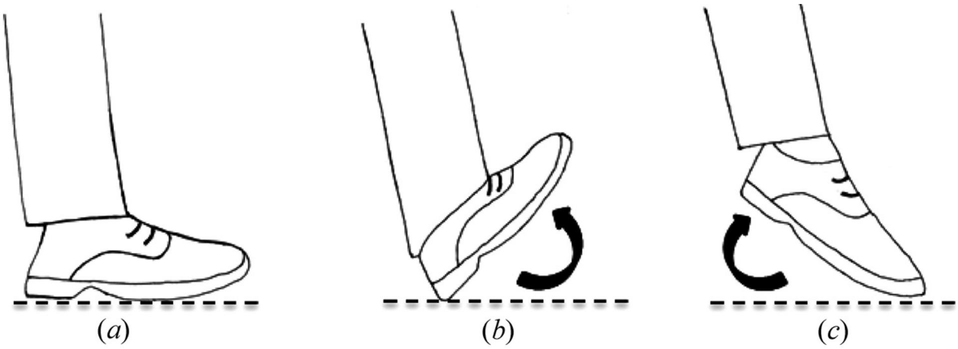


Figure 1. Schematic representation of leg in normal, ankle in dorsiflexion and ankle in plantarflexion postures.

subjects have been briefed with the details of the experiments such as the method of mounting of the sensors, exercises to be performed etc.

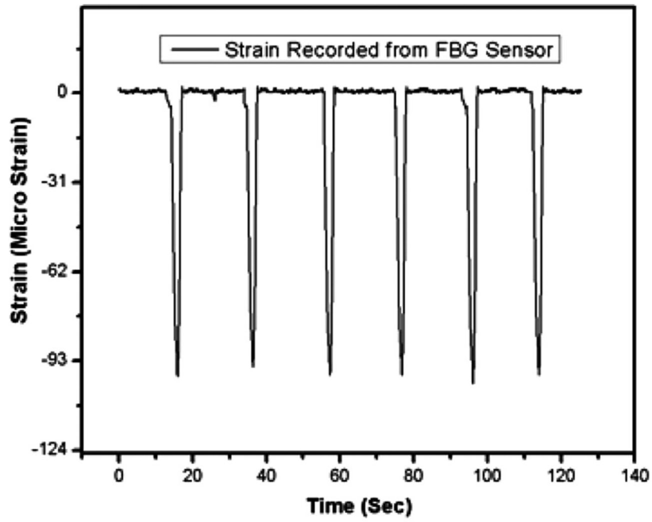
iii. **Sensing Procedure**

Volunteered subjects had been suitably instructed about the preset protocols of the experiment and detailed procedure of the exercise. The subjects were asked to sit on a chair with their foot comfortably resting on the floor. All the participating subjects were guided to perform dorsiflexion in the same sitting posture, continuously for six times with an interim gap of 10 seconds to avoid possible errors due to fatigue of the muscles; 5 minutes of relaxation time had been given before the start of plantarflexion exercise in the same sitting position.

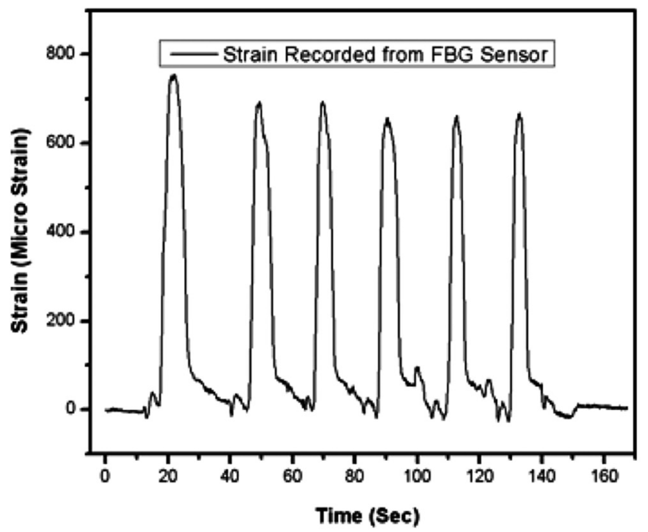
The position and placement of the FBG sensors on the calf muscle was decided in consultation with the physician during the test. A skin friendly silicon based adhesive was used as the bonding agent to bond the FBG sensor on the identified portion of the calf muscle. Because the foot print of the FBG sensor is very small, few micrograms of the adhesive is generally sufficient to bond the fiber on the skin of the calf muscle causing least possible discomfort to the subject. The signal from the FBG sensor bonded on the calf muscle was analyzed using a FBG interrogator. The FBG interrogator directly measures the shift in the wavelength of the reflected light due to the local deformation of the sensor caused by the exercise. This wavelength shift was calibrated to obtain the respective strain on the sensor bonded area of the calf muscle.

4. FBG SENSOR DATA ACQUISITION AND SAMPLES ANALYSIS

Data in real time was recorded at 1 kHz sampling frequency with the fabricated FBG sensors, using a commercial FBG sensor interrogation system (Micron Optics SM-130), with a strain resolution of 1 micro strain on the calf muscle, during the exercises. Figure 2 shows the dynamic strain generated on the medial head of the gastrocnemius muscle for a typical subject performing the specified exercises. The interim relaxation phase (approximately 10 seconds) while performing the exercise can also be observed in the Figure 2.



(*a*)



(*b*)

Figure 2. Real time strain response of FBG sensor for a sample trial of ankle dorsiflexion and ankle plantarflexion exercises.

Figure 2*a* shows the nature of strain generated on the calf muscle as compressive with negative values during dorsiflexion. A peak strain of 95 micro strain was generated for the sample trial of a typical subject. Figure 2*b* shows that the nature of strain generated is tensile showing the positive values during plantar-flexion. In the trial shown for plantarflexion, a peak strain of 736 micro strain has been recorded on the surface of the calf muscle. From Figures 2*a* and Figure 2*b*, it is seen that the strain values are consistent with each repetition, indicating the reliability of

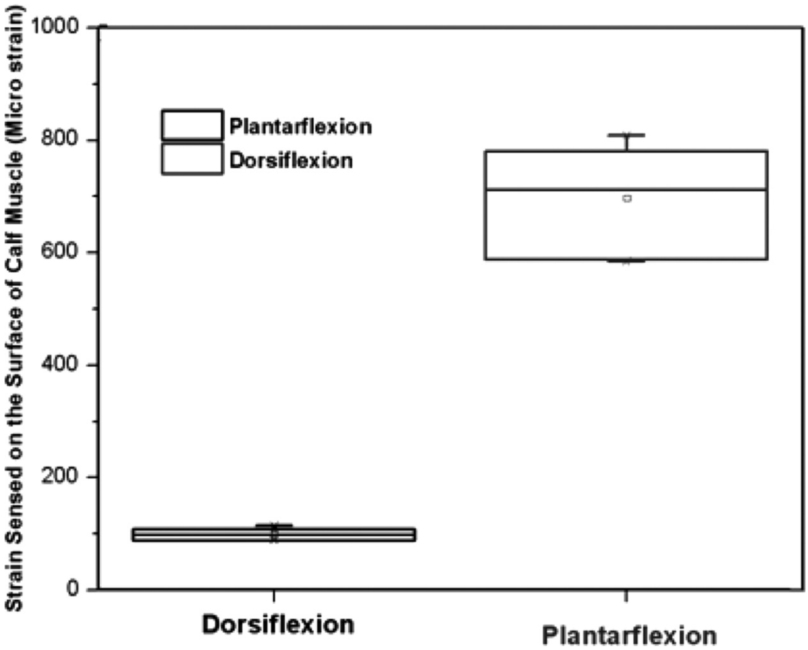


Figure 3. Distribution of strain values for all the subjects during ankle dorsiflexion and ankle plantarflexion exercises measured by FBG sensors.

the FBG sensors for muscle strain measurements. Similar trends have been observed with all other volunteers.

The average strains (absolute values) for all the six trials have been computed both for dorsiflexion and plantar-flexion. As ten subjects participated in both ankle dorsiflexion and plantarflexion exercises in this study, a box plot representation is used as shown in Figure 3, which enables the summarizing of all the data measured on an interval scale, helping to compare different sets of measured data values. Figure 3 shows the shape of the strain distribution, mean, median, and the percentile ranges for better analysis and comparison. From this plot, it can be observed that the variance in strain values in plantar-flexion is large compared against the dorsiflexion. Also, the median value of strain generated by dorsiflexion is nearly 100 micro strain, while for plantarflexion it is about 700 micro strain. These statistics can be taken as an indicative measure of the effectiveness of the exercise in generating surface strain on a particular part of the body.

5. COMPARISON WITH COLOR DOPPLER ULTRASOUND (CDU) SYSTEM

CDU is a medically proven technique which provides dynamic-color-flow vascular image of the target (Middleton et al. 1988; Mitchell et al. 1987). This technique is frequently used where blood velocity inside the veins need to be recorded during intermittent pneumatic compression of calf muscle (Nose et al. 2010; Delis et al. 2000; Lurie et al. 2003). In the present work, the CDU technique has been used for measurement of blood velocity in femoral vein while performing exercises. The subjects have been prepared to perform ankle dorsiflexion and ankle plantarflexion exercises with the CDU test probe exactly placed against the femoral vein on the thigh by a radiologist (Yoshida et al.1998; Foley and Erickson 1991). Doppler scans have been obtained from the CDU test while performing the set of exercises, which are shown in Figure 4*a* and Figure 4*b*. Figure 4*a* shows the recorded blood velocity scan during a typical subject performing ankle dorsiflexion. Similarly Figure 4*b* shows the blood velocity scan during ankle plantarflexion. As the subjects were advised to repeat the exercise for two times consecutively, two distinct curves can be observed in these figures. It can be seen from Figure 4*a* and Figure 4*b*, that peak

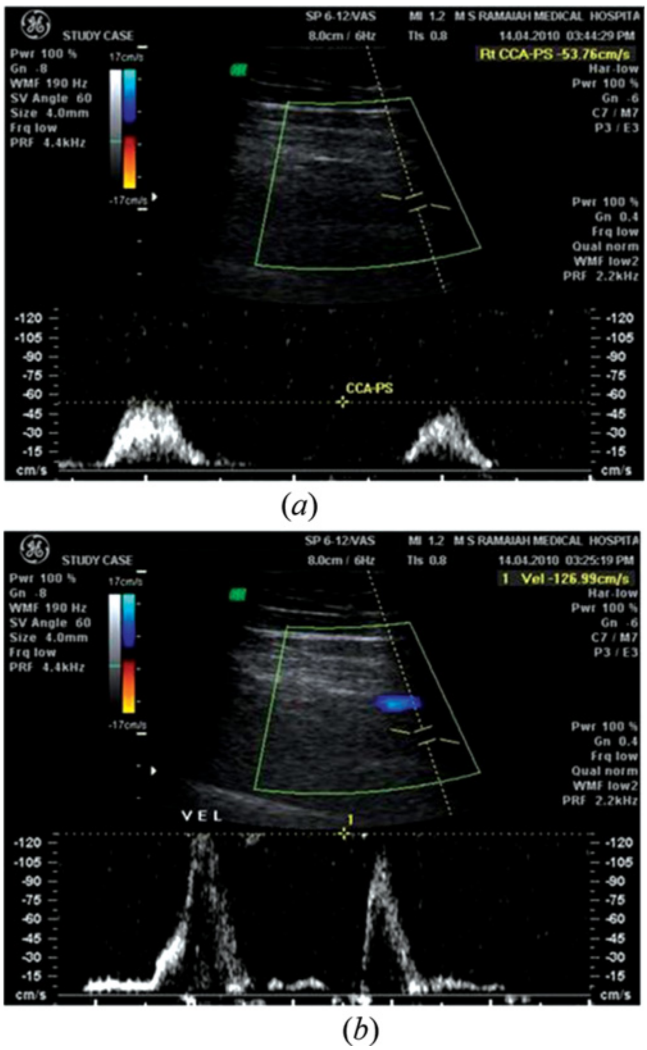


Figure 4. Color Doppler ultrasound scans for a typical subject performing ankle dorsiflexion and ankle plantarflexion exercises (color figure available online).

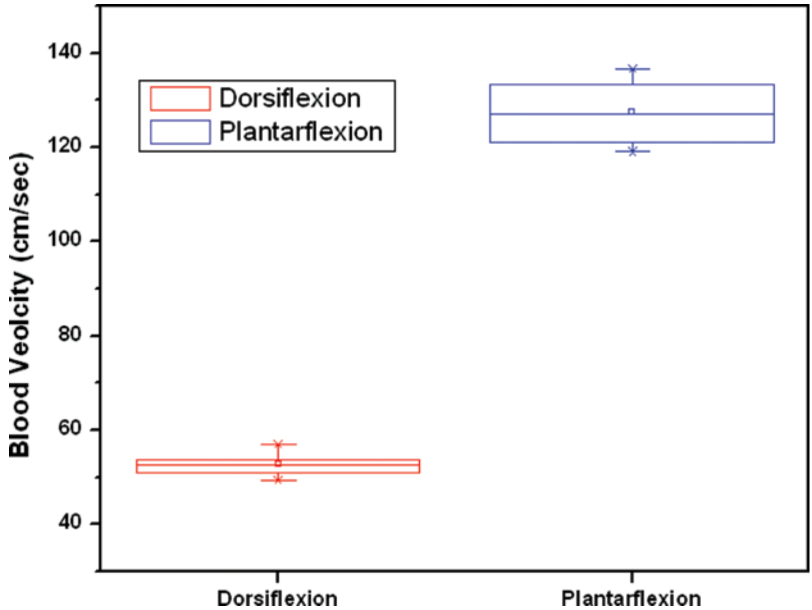


Figure 5. Box plot of blood velocities from color Doppler ultrasound system for ankle dorsiflexion and ankle plantarflexion exercises (color figure available online).

velocities of 53.7 cm/sec and 126.9 cm/sec have been recorded. These blood velocity variations obtained by all the ten volunteered subjects are plotted on a box plot and shown in Figure 5.

Comparing the results obtained from FBG sensors (Figure 3) and CDU system (Figure 5), it is evident that there is a good correlation between the strain values measured by FBG sensors and the blood velocities measured by CDU. Further, the strain values and the change in blood velocities for dorsiflexion are comparatively lesser than that of the plantarflexion exercise. This match in trend between the proposed methodology based on FBG sensors and the CDU system depict the fact that FBG sensors can be reliably used for measurement of surface strain in biomechanical applications involving human beings.

6. CONCLUSIONS

This article brings out the utility of non-electrical, non-invasive, and easy to use FBG sensors for the measurement of strain on the superficial muscles of humans, during variety of physical exercises. Successful demonstration of the technique is done by measuring the strain on the medial head of the gastrocnemius muscle during dorsiflexion and plantarflexion. The measurements have been undertaken on ten different subjects with six trials for each exercise. The results obtained show that the FBG sensors have excellent consistency and reliability in the measurement of muscular strains. The results from the FBG sensors have also been compared against the medically proven CDU system and found to be in good agreement. As the foot print of the FBG sensors is very small, they can be bonded easily on the skin of the muscles without causing any discomfort to the subject. Also, the multiplexing capability of the FBG sensors allows the usage of several FBG sensors on the same fiber to measure strains at different/small portions of any superficial muscle simultaneously.

Though the present experiments clearly indicate the usefulness of FBG sensors in surface strain measurements on skin, there are still certain challenges to be addressed while using FBG sensors in bio-mechanical applications; these include the use of proper skin-friendly bonding agents, the usage of packaged FBG sensors rather than using the bare FBG sensors, etc.

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