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Stability Test of the Silicon Fiber Bragg Grating Embroidered on Textile for Joint Angle measurement

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ABSTRACT

Recently, Fiber Bragg Grating (FBG) sensors are being used for motion tracking applications. However, the sensitivity, linearity and stability of the systems have not been fully studied. Herein, an embroidered optical Fiber Bragg Grating (FBG) on a stretchable supportive textile for elbow movement measurement was developed. The sensing principle of this system is based on the alteration of Bragg wavelength due to strain from the elbow movements. The relationship between elbow movements and reflected Bragg wavelength was found to be linear. The dynamic range of FBG sensor on elbow support is between 0 and 120 degree. Finally, the stability of the FBG sensor on the supportive textile was tested during the exercise and the cleaning process with water. The sensitivity of FBG sensors for joint angle measurement and the effect of the movement and cleaning process to signals from FBG sensors after using in the real activity will be the basis knowledge for design and actual implementation of future optical fiber based wearable devices.

Keywords: Fiber Bragg Grating, Goniometer, Optical Fiber Motion Tracking, Wearable Textile Device

1. INTRODUCTION

The development of the advance technology including nanotechnology, material science, and electronic technology lead us to the smart textile wearable devices [1]. Most of the smart textiles, normally called “wearable electronic” are developed based on electronic system [2, 3]. These devices can monitor the physiological condition of our body [4, 5], communicate via the wireless system [6], and generate power by themselves [6, 7]. Therefore, the applications of the smart wearable are broad from the aesthetic fashion garment to data processing in the continuous monitoring purposes. For continuous monitoring, the interface between the users and the devices is critical. The users should be comfortable to equip or wear the smart textile, and the devices should not cause adverse effects or limit the motions of the user. Moreover, in the context of the user-interface, the movement and the secretion from the users, (e.g. sweat, saliva, urine) and the laundry process can deteriorate the integrated system inside the electronic smart textiles [8].

To overcome these challenges, photonic systems are alternative for smart textiles [9]. Photonic systems are gaining interest during last decade because optical-based sensors have low interferences of signal from electromagnetic wave, high data bandwidth, and no hazard from optical wire. Normally, smart optical textiles could be used in high electromagnetic fields especially during the magnetic resonance imaging examination (MRI), because of their immunity to the electromagnetic field [9-11].

One of the common fiber optic sensors is Fiber Bragg Grating (FBG), which is usually used in the industry and automotive field as a strain sensor [12] and temperature sensor [13]. Theoretically, the Bragg wavelength was based on

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

; where λ_B is Bragg wavelength, n_{eff} is effective refractive index of the core, and Λ is fiber grating period

Since effective refractive index and fiber grating period are affected by both strain and temperature, the Bragg wavelength shift is governed by

$$\Delta\lambda_B = 2\left(\Lambda\frac{dn_{eff}}{dT} + n_{eff}\frac{d\Lambda}{dT}\right)\Delta T + 2\left(\Lambda\frac{dn_{eff}}{d\epsilon} + n_{eff}\frac{d\Lambda}{d\epsilon}\right)\Delta\epsilon \quad (2)$$

; where $\Delta\lambda_B$ is bragg wavelength shift, ΔT is temperature variation and $\Delta\epsilon$ is strain variation.

Currently, the FBG sensors are integrated in the smart textile to monitor the physical conditions, for example, respiratory rate, heart rate and body temperature [14-16]. The FBG sensors are usually attached firmly to the patient; for example, sensors are placed at the chest of the patients [14, 16] or the patients lay on the sensor [15]. However, there are a few FBG sensors in the motion analysis applications [17, 18].

As aforementioned, the movements and alterations of the environment on the surface of the fiber are crucial factors for the smart textile development. The bending of the fiber can reduce signal performance of the fiber [19]. In our daily life, the movement of body joint causes micro- and macro- bending of the optical fiber. The sweat from our body, humidity from the environment and cleaning process can cause degradation on the protective layer of the fiber. These factors are rarely found in MRI examination and in the structural sensing device. Therefore, the effect of movement, sweat absorption, cleaning process on the signal from FBG sensors in real activity will be the basis knowledge for other optical-based wearable devices.

Herein, FBG sensors with Bragg wavelength (1541 ± 0.5 nm) were integrated with stretchable supportive textile and were applied on elbow of the participant. The movement of the elbow angle can induce strain inside the FBG sensors and cause the Bragg wavelength shift. The relationships between the Bragg wavelength shift and elbow joint angle were studied. To test the FBG sensors realistically, the participant was made to run on treadmill at 9 km/hour for 30 minutes. After exercising, the FBG sensors were cleaned with tap water to simulate the cleaning process. Finally, the signals from FBG sensors were compared before and after exercising and cleaning process. The proper design, effect of the joint movement, sweat and cleaning process were discussed in this study.

2. METHODOLOGY

Single mode FBG sensors coated with acrylic (Technica Optical) were used in this experiment. The core diameter/fiber diameter is $9.5/125$ μm and the Bragg wavelength is 1541 ± 0.5 nm. The light source in this experiment is ASE (Amplified Spontaneous Emission) generated Erbium-Doped Fiber Amplifier (EDFA) (Opto-link corporation). These light sources provide incident light power ~ 2 mW at wavelength 1539-1543 nm. The reflected Bragg wavelength is detected by Optical Spectrum Analyzer (AQ6370C OSA, Yokogawa Electric). The light source, FBG sensor, and OSA are connected via optical circulator (Thorlabs, Inc.). The experimental setup is illustrated in Figure 1.

Figure 1. Schematic of FBG goniometer system. The FBG sensor was directly stitched onto the stretchable elbow support.

2.1 The study of suitable FBG sensors design on elbow support for elbow angle measurement

The first important factor of the FBG goniometer design is FBG sensors alignment. The alignment of FBG sensors will affect the wearability of the overall system. Since FBG sensors are fragile, bending beyond the bending radius can damage the grating structure inside FBG and can break the fiber instantly. Moreover, bending of the FBG sensors cause a loss of light power inside the fiber. Proper alignment of the fiber on the elbow support was optimized to prevent the fiber damages and to get repeatable signals from FBG sensors. Two different designs of the FBG sensors were stitched on elbow support (Figure 2.). Then, the subject wear the elbow support and start moving from full extension position (0 degree) to full flexion position (120 degree). The signal from FBG sensor were recorded by OSA.

Figure 2. Two different designs of FBG sensors embedded on stretchable elbow support: (a) straight design and (b) curve design.

2.2 Sensitivity study of the embroidered FBG on elbow support

To study the sensitivity of FBG sensors, the curve design of the FBG sensors was select to stitched FBG sensors onto the substrate. The FBG sensors were fixed firmly by tape to increase the robustness of the systems. The goniometer was used to measure the angle of the elbow from full extension (0 degree) to full flexion (120 degree). FBG sensor was worn on medial side of the elbow, while goniometer was attached on lateral side. The data were recorded from OSA every 10 degree. Three separate readings were taken at each angle setting.

Figure 3. Elbow joint angle measurement by using (a) goniometer on lateral side and (b) FBG sensor on medial side of the elbow

The wavelengths at the peak power of the reflected light, called “Bragg wavelength”, were measured and averaged from the data sets. The shifting of the Bragg wavelength due to the elbow joint movement was calculated by Equation 3.

$$\Delta\lambda = \lambda_i - \lambda_0 \quad (3)$$

; where $\Delta\lambda$ is Bragg wavelength shift, λ_i is reflected Bragg wavelength at any degree and λ_0 is the reflected Bragg wavelength at 0 degree

Finally, the Bragg wavelength shifts and the corresponding angles were plotted to find the sensitivity of the system.

2.3 Sensitivity comparison between FBG on elbow support before and after exercising and cleaning

To test the stability of the FBG goniometer systems, sensitivity comparisons between before exercise and after exercise and cleaning were studied. The FBG goniometers were worn on the subject's elbow. Then, he was made to run on treadmill at 9 km/hr for 30 minutes to simulate the exercise condition in real environment. For the cleaning protocol, the sensors were cleaned by tap water and dried at room temperature for 24 hours. Finally, the FBG sensors were measured by the method described in Section 2.2.

3. RESULTS AND DISCUSSIONS

3.1 Optimum design study of the FBG sensors for elbow joint angle measurement

The average central Bragg wavelength from the straight design at full extension and full flexion were 1540.76 nm and 1540.83 nm respectively, while the average central wavelength from curve design were 1540.72 nm and 1540.82 nm respectively. Both designs can be possibly used for patterning FBG sensors on the elbow supports. In studying of the wearability of the system, the fiber with straight design tends to break by the folding of the textile. In contrast, the curve design has more the flexibility. Thus, it can prevent the fiber from breaking under suck in the elbow support. Therefore, the curve design was selected for further study.

3.2 The sensitivity of the FBG sensors to the elbow joint angle

The Bragg wavelength shifts were increased corresponding to the elbow angle as displayed in Figure 4. These results resembled the report from R.P. Rocha et al. [17] Their system embedded FBG inside PVC foil and tested on knee. The maximum Bragg wavelength shift was 400 pm between flexion and extension stage. They also found small variation between these two positions. From these results, they suggested that it was possible to obtain the relationship between the Bragg wavelength shifts and the joint angles. By using our system, the relationships between elbow angle and Bragg wavelength shift were found to be linear as shown in Figure 5. The Bragg wavelength shift was approximately 60 pm between elbow joint angle 0 – 120 degree. Thus, the sensitivity of the system was ~ 0.5 pm/degree.

It should be noted that the lower Bragg wavelength shift from our design, compared with R.P. Rocha's system, was due to different designs. The embedded FBG in PVC foil in their system can improve the sensitivity of their system [20]. On the other hand, the advantage of our system was the linear response between Bragg wavelength shift and joint angles. Moreover, by direct stitched FBG sensors on flexible textile, this method was more flexible for optical-based wearable device development.

Figure 4. The Bragg wavelength shift before (left) and after (right) exercise and clean

Figure 5. The relationship between the elbow angle and Bragg wavelength shift before (left) and after (right) exercise and clean

3.3 Repeatability and reliability of the FBG goniometer system

a) The repeatability of the Bragg wavelength shift

As shown in Figure 5, the challenge of these system was the repeatability of the system. The responses from FBG goniometers were not repeatable although the sensors were firmly fixed on the support and put on at the medial side of the elbow. The reason of these variations could be the stretchability of the textile. Since the FBG sensors were integrated onto stretchable elbow support, the stretchable textile will adjust its shape to fit the elbow. Thus, it was difficult to tie down the location of the sensors at the exact location all the time. Moreover, after repeated exercise and cleanup, the textile will deform and loosen overtime. This is a common challenge of the smart textile development [2]. Therefore, further study should be focused on the improvement of the textile or flexible substrate to reduce the signal variations and prolongation of the system lifetime.

b) Different of the Bragg wavelength before and after exercising and cleaning

The Bragg wavelength was changed after exercise and cleaned by tap water as shown in the Bragg wavelength in different region in Figure 4. One possible reason was the temperature difference (ΔT) because of the measurement was done at different time. Another possible reason was the pressure between the stretchable textile and the muscle. Because the stretchable support created pressure between FBG sensor and elbow, this pressure was translated into strain in FBG sensors through Poisson's ratio. When the stretchability of the elbow support changed after use, the strain in the FBG sensor will be also changed ($\Delta \epsilon$). Therefore, from Equation 2, if the measurement done on different times, or on different subjects, both the temperature difference (ΔT) and the strain difference ($\Delta \epsilon$) will cause change in the Bragg wavelength.

To solve this problem, recalibration of the sensors should be done with using Equation 3 every time before starting joint angle measurements. The Bragg wavelength at 0 degree will be the reference wavelength for comparison with the other wavelengths from the other angles. By using this method, despite changing Bragg wavelength in every measurement and situation using the FBG sensors, the relationship between elbow angle and Bragg wavelength shift was almost same as shown in Figure 5. It shifted approximately 60 pm over 120-degree movement with sensitivity 0.5 pm/degree. Therefore, the consistency increasing of wavelength shift and linearly response from FBG sensors showed the potential of the FBG sensors to be used as optical goniometers.

4. CONCLUSIONS

FBG sensors had potential for the joint angle measurement by directly embroidered on the stretchable textile. The curve design was suitable for joint angle sensor because it can prevent the fiber from breaking. The elbow movements, sweat and cleaning process changed shape and flexibility of the support textile. These deformations of the textile created the variation to the system and altered the Bragg wavelength from the FBG sensors. We can avoid those problems by simple calibration the sensors before measurement. The sensor responses were found to be linear with sensitivity 0.5 pm/degree from between joint angle 0 – 120 degree. Further study should be focus on the improvement of the robustness of the system to improve repeatability of the sensors and prolong lifetime of the sensors.

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