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FBG in PVC foils for monitoring the knee joint movement during the rehabilitation process

R. P. Rocha, A. F. Silva, *Student Member, IEEE*,

J. P. Carmo, *Member, IEEE*, J. H. Correia, *Member, IEEE*

***Abstract*—This paper presents a sensing electronic-free wearable solution for monitoring the body kinematics. The measuring of the knee movements, flexion and extension, with the corresponding joint acting as the rotation axis is shown as working principle. The proposed sensing system is based on a single optical Fiber-Bragg Grating (FBG) with a resonance wavelength of 1547.76 nm. The optical fiber with the FBG is placed inside a new polymeric foil composed by three flexible layers which facilitates its placement in the anatomic parts under investigation while maintaining full sensing capabilities. The way the device is placed in the specific body part to be measured enables the clear detection of the movements in respect to the joint. The proposed solution was tested using a prototype that was built to evaluate the device under different condition tests and also to assess the system's consistency. The designed and fabricated system demonstrates clear advantages in medical fields like physical therapy applications as optical fiber is not affected by electromagnetic interference nor does the system needs complex and expensive electronic systems and mechanical parts. Another advantage is the possibility to measure, record and evaluate specific mechanical parameters of the limbs' motion. Patients with bone, muscular and joint related health conditions, as well as athletes, are within the most important end-user applications.**

I. Introduction

THE necessity for monitoring the different body kinematics [1] in human beings is a growing area within the field of engineering applied to medicine. Universities, high-performance sport centers and health-care institutions have been investing in developing ways to measure and evaluate accurately the way the human body moves for endless purposes. The main objectives for such attention in body kinematics were the further improvements of athletic performance [2] in competitions and to study the historic evaluation of patients to determine if the prescribed therapy is being efficient or not. Different systems for monitoring the body kinematics have been realized using different approaches such as complex electronic systems including a 2.4 GHz radio-frequency (RF) transceiver [3], advanced software algorithms that demand profound specific know-how and are also very complex and motion capture techniques [4,5]. Other applications for member monitoring include the assessment of certain neurologic diseases [6,7].

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R. P. Rocha, A. F. Silva, J. P. Carmo and J. H. Correia are with the University of Minho, Dept. Industrial Electronics, 4800-058 Guimarães, PORTUGAL. R. P. Rocha is the corresponding author: +351-253-510190; fax: +351-253-510189; e-mail: rrocha@dei.uminho.pt and is supported by the Foundation for Science and Technology with the financial grant SFRH/BD/33733/2009.

II. System Design

The proposed system is composed by a sensing and monitoring part. Figure 1 shows the photographs of the light source, and the hardware used in the interrogation system, for monitoring the received light which is seen on a computer screen. The Fiber-Bragg Grating utilized in these experiments was produced by the company FiberSensing [8]. The length of the grating is 8 mm corresponding to a resonance wavelength of 1547.76 nm. This wavelength corresponds to a refraction index modulation period of the core in the half-micrometer range. The interrogation monitor (I-MON 80D from Ibsen Photonics [9]) allows real-time spectrum monitoring of FBG sensors interrogation systems. With the interrogation monitor a software is supplied by the manufacturer that allows the visualization of the obtained waveforms in a computer, in real-time, while the sensor is being actuated.

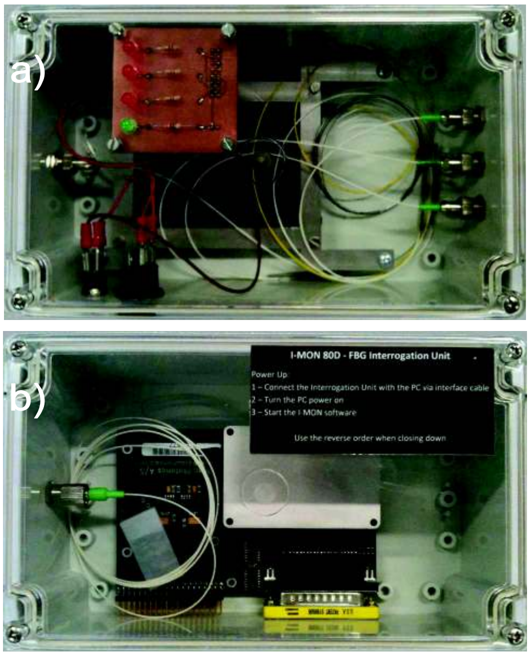

Figure 1 – Proposed system's non-sensing parts composed by a) light source [10] and in b) the optical circulator [11] and interrogation monitor hardware [9].

This data can be saved for further investigation and study which allows comparisons to be made along the time. The other target goal of the proposed system was to obtain maneuverability for making it compatible with free range body kinematics movements.

A. Approach

The knee kinematics is represented by two stages: flexion and extension. The objective is to represent graphically, as a function of the measured wavelength, the full human gait period, centered on the knee joint using just one FBG and a single mode optical fiber. Since the focus of this paper is the validation of the proposed concept by measuring the knee's kinematics, this single fiber and single FBG sensor, placed in the center of the knee, are enough to measure and evaluate the subject's evolution. In order to make this possible, a high-sensitivity sensor is necessary to detect the full movement from one extreme (when the leg is completely straight) to the other (maximum knee deflection during gait) and all movements that happen in-between, *i.e.*, stance and swing phases. The sensing part is based on a flexible structure that can be placed/removed on/from the knee very easily. This is done by using small pressure buttons as bonding elements. Figure 2 shows in more detail the small metallic pressure buttons that attach the different components of the sensing system, the elastic knee band already placed and the foil with the embedded FBG. This type of elastic knee band is regularly used in prevention/precaution situations in people with a temporary or permanent muscular injury. This enables the use of the flexible structure by any person and in any junction in the body. The pressure buttons ensure that the sensing element is able to transduce the flexion and extension of the knee as the subject moves around.

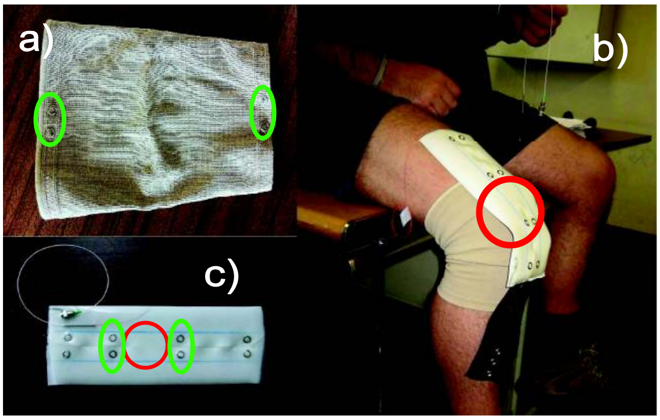

Figure 2 – In a) the elastic knee with the pressure buttons signaled with green ellipses. In b) the sensing part attached to a standard elastic knee band and in c) a close-up just of the PVC foil with the embedded FBG signaled with a red circle and the pressure buttons with green ellipses.

Since optical fibers are immune to electromagnetic interference (EMI) and can be used safely in wet environments or even under water, the proposed solution increases the number of possible applications for this technology.

B. FBG Sensor

A wide variety of optical fiber sensors are available, which can be divided into three categories: The external or extrinsic ones where the fiber is only used to transfer the measured information to a distant location [12], the intrinsic category where the optical properties are sensitive to strain and temperature [13], and the hybrid category where the light is transferred over the optical fiber for conversion into electricity on a distant optical receiver [14]. From the previously mentioned categories, the intrinsic sensors, where FBGs are included, have been studied and applied intensively during the past 20 years [15]. The Bragg grating structure is the intrinsic element to the fiber responsible for the sensor behavior. The gratings can be inscribed by ultraviolet (UV) light beams due to the photosensitivity of the optical fiber (doped with germanium) to this radiation. Besides the standard advantages attributed to the optical fiber sensors, FBGs have an inherent self-referencing and multiplexing capability. Essentially, the FBG is a periodic variation of the refraction index along the fiber axis. This structure works as a reject-band filter, reflecting back the spectral component, λ_B [nm], which satisfies the Bragg condition (given by the equation (1)) and transmitting the remaining components. The Bragg wavelength is given by [16]:

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

where Λ is the grating pitch and n_{eff} is the effective refraction index of the fiber core. The wavelength shift, $\Delta\lambda_B$ [nm], of a FBG sensor subject to a physical disturbance is given by [17]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-\rho_e)\Delta\varepsilon + (\alpha+\xi)\Delta T \qquad (2)$$

where ρ_e, $\Delta\varepsilon$, α, ξ, and ΔT are the effective photoelastic constant, the axial strain, the thermal expansion, the thermal optic coefficient and the temperature shifts, respectively. The ratio in the first term of the equation (2) expresses the strain effect on an optical fiber. It corresponds to a change in the grating spacing and the strain-optic induced change in the refractive index. The temperature sensing is related with the second term of the expression. As the FBG is subjected to temperature variation, it dilates or contracts, modifying the grating pitch.

C. Flexible Sensing Structure

The accurate measurement of the knee joint movement is possible after increasing the sensitivity of the sensor. This was done by properly selecting the substrate material that can transduce correctly the actual movement. A structure with enough area to cover the knee would enable the transference of the movements to the embedded sensor. A wide rectangular configuration was chosen to better cover both the flexion and the extension movements because it provides the required area of contact to be translated by the sensing area and allows the light to travel without any abrupt corners that would obstruct the communication with the monitoring stage. The main characteristics, and advantages, of this foil include the flexibility, the stretchability and the capability to sustain a good bonding between the optical fiber and the substrate. The host material is polyvinyl chloride (PVC) with custom formulation to assure the bonding and the stimulus transfer. Moreover its size and shape are completely customizable during fabrication.

III. Results

A. Capabilities of the system

The measurement was done with the subject walking and running on top of a commercially available treadmill found in gymnasiums with the prototype having the sensor embedded in the PVC foil attached to an elastic knee band. Different types of walking and running were measured to evaluate the system's consistency and reliability. Moreover, the way that the optical fiber is attached to the knee band was also evaluated and is considered "user-friendly" by the subject. No obstructions or difficulties were sensed by the subject in all types of tests performed showing that the system is flexible enough to be used in other environments. Figure 3 shows, as an example of the system's capability, two waveforms of some tests performed under different speeds, at 0.8 km/h and 8 km/h. The tests were done during 10 seconds but only 5 seconds are considered for clear visualization of the acquired data.

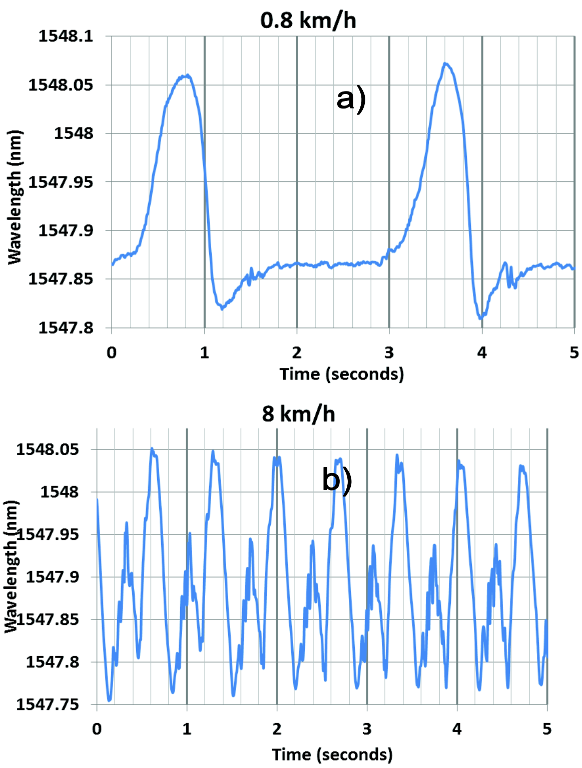

Figure 3 – Measured wavelengths values for a calm walk at 0.8 km/h and a run at 8 km/h.

From the previous plots representing the acquired measurements, it can be seen that with the current prototype, the waveform is smoother at low speeds than in high ones because the elasticity factor of the knee band influences slightly the position of the FBG in the knee. This means that the elastic band matches perfectly the skin when moving slowly. The vibration caused by the running steps is also a source for the somewhat abrupt peaks in the waveform at 8 km/h. Different sizes of the elastic knee band and the way it is attached to the foil with the embedded sensor can also reduce these fast oscillations, even though the reference extreme points are still very visible.

B. Measured signal versus gait description

Two sessions with different speeds were measured with simultaneous video recording for comparison purposes. In order to compare the period of the measured waves to the different stages of a full step, Figure 4 shows the two extreme values obtained by the system during a complete step and 2.5 seconds of measured output data on a test done at 4 km/h. It can be seen the stage where the flexion of the leg in the knee joint, hence on the FBG as well, is minimum during a full step which corresponds to the value of 1547.76 nm. In Fig. 4b) is represented the maximum deflection obtained during a step corresponding to the value of 1548.16 nm.

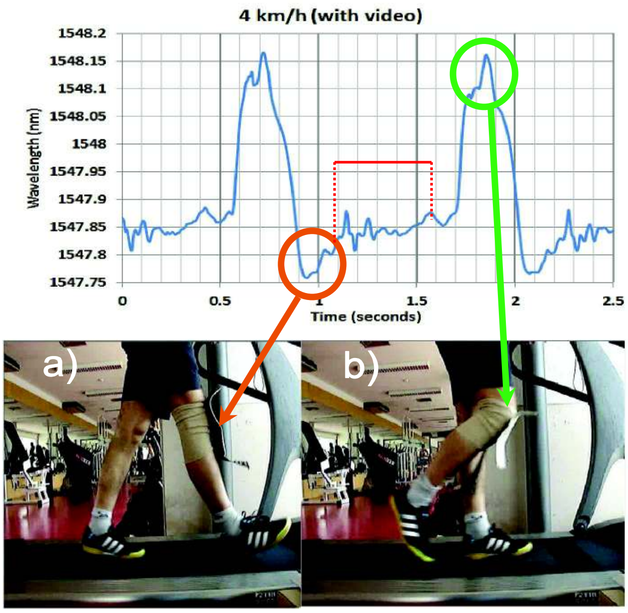

Figure 4 – Measured values for a walk at 4 km/h. In a) and b) it is seen the minimum and maximum deflections of the FBG, respectively.

It should be noted that between the minimum and maximum values, the leg is always touching the floor (stance phase) and is basically completely stretched with just minor variations related to the elastic knee band used. This relatively constant period is pointed out in red in the chart seen in Figure 4. In Fig. 4a) the right leg is starting its movement backwards touching the floor first with the ankle, proceeding with the base of the foot until it begins the movement forward with the tip of the toes (beginning of the swing phase). The sharp rise found in the periodic wave corresponds exactly to that specific moment.

IV. CONCLUSIONS

This paper presented a monitoring system based on a single optical fiber sensor for monitoring the knee joint movement during human gait. A structure made of polyvinyl chloride (PVC) material, carrying an embedded Fiber Bragg Grating (FBG) sensor, was attached to a knee band and used as a prototype. A clear characterization of the movement of the knee joint as a function of the wavelength was achieved. All the different movements associated with a full step, the stance and swing phases, are clearly identifiable in the obtained waveform allowing comparison between different results acquired in different situations. Future work concerning the presented waveforms is to associate them to the knee joint angle. Thus it is possible to obtain a relation between the aforementioned measurands (nanometers and degrees) to make the system even more user-friendly for non-specialist end-users. The presented solution for the knee is also possible for any other joint in the human body. An elastic band is the only requirement to serve as substrate and adapt the system to the PVC foil. As explained in II A, the presented prototype is easy to connect and does not require technical personnel to give support and expertise making this approach very interesting as a functioning system for body kinematics monitoring. Moreover, since optical fiber is immune to electromagnetic interference and can support wet environments, including under water, the developed system opens new applications for body kinematics monitoring. Not only this is useful for health evaluation associated with limbs and joints but it also presents as an athlete's support to check if there have been advancements in a specific scheduled type of training and exercises. The integration of a single optical fiber in a polymeric foil made of PVC resulted in a structure with a good sensitivity for transducing accurately the knee flexion and extension during the walking and running tests.

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