Knee Joint Movement Monitoring Device Based on Optical Fiber Bending Sensor

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***Abstract*—This paper discusses the possible implementation of an optical fiber bending sensor for knee joint monitoring application. The studied technique is based on the use of an intensity modulated optical fiber via angular displacement between two separated fibers, which approach has been implemented previously in spine movement and respiration rate measurement. To estimate the suitability of this technique for knee monitoring application, the maximum range of detection of the sensor is estimated using the output intensity equation for plastic optical fiber. Based on the estimated output intensity graph with respect to bending angle, it is concluded that the aimed technique is not perfectly suitable for the knee monitoring due to limited sensor's range of motion, which renders a limited the sensor detection range for knee joint movement. In addition to this, several other types of knee joint monitoring devices are also presented and summarized in a table form to highlight the contribution of other devices.**

***Index Terms*—Health Monitoring; Knee Injury; Knee Monitoring; Optical Fiber Sensor.**

I. INTRODUCTION

Health monitoring applications for human cover different body areas such as respiration assessment, heart rate monitoring, gait monitoring, heart rate monitoring, glucose level measurement as well as lower and upper limb motion detections [1]. Among all joint movements related to the lower limb motion, the knee joint is considered among the most important and critical health assessment due to the high exposure of this area to injuries. Knee problems and injuries most often occur during sports or recreational activities, work-related tasks, or home projects.

The knee is the largest joint in the body [2]. The upper and lower bones of the knee are separated by two discs (menisci) [3]. The upper leg bone (femur) and the lower leg bones (tibia and fibula) are connected by ligaments, tendons, and muscles. Figure 1 illustrates the typical range of motion of the human knee. The surface of the bones inside the knee joint is covered by articular cartilage, which absorbs shock and provides a smooth, gliding surface for joint movement. [2, 3].

Many heavy jobs, sports and recreation activities, getting older or having a disease such as osteoporosis or arthritis increase the chances of having knee problems. Sudden (acute) knee injuries may be caused by a direct blow to the knee or from abnormal twisting, bending the knee, or falling on the knee [4].

Based on a 7-year study among sports athletes in 12 different sports in Europe county, involving 3864 knee injury cases, it was found that female athletes were significantly at risk in six sports; alpinism, downhill skiing, gymnastics, volleyball, basketball and handball. Meanwhile, male athletes were more exposed to a knee injury in sports activities such as ice-hockey, handball, soccer, downhill skiing and basketball. In this study, it was summarized that knee injuries from sports activities comprised 10% of all injuries in males and 13% in females [5]. Most knee injuries are similar and often related either to the lack of training or to overuse and fatigue. It was also important to note that most knee injury persons are between 20 to 29 years old (50%). This statistics was published from a 10-year period on a study among athletes aged between 10 to 69 years old [6]. These findings highlight the needs for the reliable device at low operational cost by researchers in the biomedical field so that the aimed users (e.g. physiotherapist) can have more alternative devices in knee injury treatment and recovery.

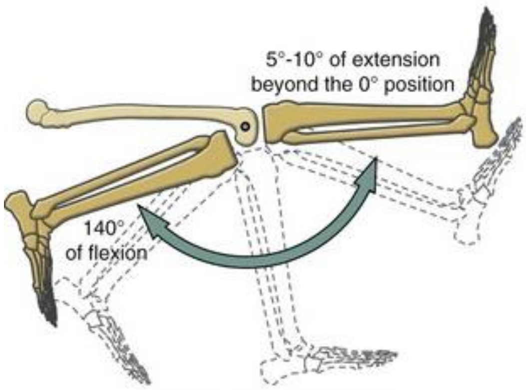

Figure 1: Illustration of human knee range of motion [4]

Although it is possible to prevent knee injuries from sports activities [7], there are little options that can be done for athletes especially when they involve in tight schedules of training and tournaments. For this reasons, health practitioners and physiotherapists are inconsistently suggesting different approaches to knee injury treatment among athletes. Among these options are dietary intervention, exercise, drug therapy and surgical interventions [8]. Due to the adverse effects of drug therapy and the high cost of surgical intervention, intensive exercise is a popular choice for the athletes. To efficiently monitor the condition of the knee injury after each treatment, a reliable monitoring device is thus needed, so that more information on the knee condition could be retrieved by the user for further consultation and treatment.

For this reason, majorly available knee monitoring devices are discussed in details here. As far as laboratory scale tests are concerned, several different devices have been developed and investigated for this application so far, including using accelerometer [9], torsiometer [10], conductive fiber [11], and side-polished fiber optic [12]. These devices offer diverse characteristics and measurement performances, but most of them do not support in-situ measurement that is required for continuous knee assessment [13]. Moreover, in some cases such as the accelerometer device, it has quite a large overall device dimension (and weight) that could cause discomfort to device's wearer [14]. Further discussion on various types of knee monitoring devices is presented in the next section.

As an overall, the objective of this research is to develop a non-invasive knee monitoring device based on optical fiber technology. The investigated extrinsic optical fiber sensor must have a small sensor dimension, lightweight, easy to wear and require minimum experience for device handling. These advantages can be made possible due to the small fibre optic cable dimension (typically 1 mm diameter for plastic fibre) [15]. In addition, the inherent advantage of immunity to electromagnetic disturbances of the optical fibre technique also makes it suitable for high-risk application such as in hazardous places [16].

In this paper, a possible implementation of an intensity modulated optical fiber bending sensor for knee monitoring application is investigated. This approach, which uses the light attenuation resulted from the angular displacement between two separated optical fibers, has been implemented in other health monitoring applications such as spine movement [17] and respiration monitoring [18]. Due to the different background between the knee monitoring application and the above-mentioned applications [17, 18], this paper presented the output estimation of the optical fiber, in order to find the maximum range of motion of the sensor using this approach. The obtained results are critical to establish further development work of the knee monitoring devices using the investigated technique.

II. Different Types of Knee Joint Movement Monitoring Devices

The first device discussed here has been applied on elite athletes as his subjects for the study. A monitoring device called electrogoniometer is used, which comprised of optical fibres to measure motion, using a fixed end-block and a telescopic end-block [19] as illustrated in Figure 2. This study measured knee joint angles in three different starting positions which are supine, sitting, and standing [20]. The results proved that using a standardised protocol minimises measurement error, and performance was reliable. It is concluded that a flexible and lightweight electrogoniometer is reliable for the static type of measurements for knee joint angles in supine, sitting and standing postures [21].

Another method proposed by Dejnabadi. et al. [22] obtained kinematic data from gait analysis to evaluate and quantify knee joint angle. This research assists physiotherapists to decide suitable treatments for the patient. The sensors applied in this research are accelerometer and gyroscope, which are mounted on the subject's thigh and calf as close as possible to the knee joint as illustrated in Figure 3.

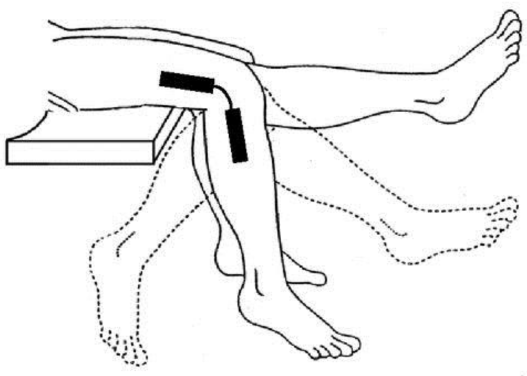

Figure 2: Knee monitoring using electrogoniometer [19]

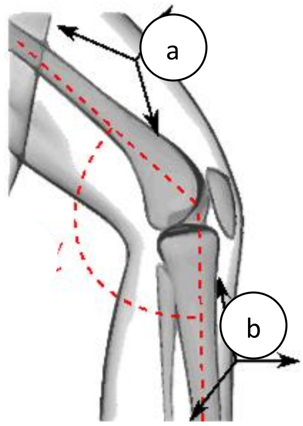

Figure 3: Knee monitoring using accelerometer at 2 locations; a & b [22]

The same sensors combination (accelerometer and gyroscope) have also been introduced to measure the angular movement of shoulder and elbow [23]. The popularity of inertial based sensor to detect human joint angle is due to its simple (straightforward) technology, unobstructed and self-contained characteristics. The accelerometer is used to provide translational and gravitational accelerations while gyroscope is for angular velocity data [24]. However, the use of the accelerometer to measure the knee angle could lead to signal drift when the subject under study is not in motion, render a poor device accuracy. The integration of gyroscope alongside with the accelerometer is also not possible to solve this problem because of rapid accuracy degradation as shown by Roetenberg. [25].

The next type of device applicable for knee monitoring is based on small three degrees of freedom sensor modules containing angular rate sensors, accelerometers, and magnetometers [26]. This sensor combination was able to eliminate the drift errors by using filter technique. However, variations in the direction of the local magnetic field reference vector can cause errors in the knee orientation, thus reducing the sensor's accuracy.

The next technique for knee monitoring application involves the use of conductive fibers into flexible, skin-tight fabrics surrounding the knee joint [27] as shown in Figure 4. Resistance changes across these conductive fibers are measured and directly related to specific single or multi-axis joint angles through the use of a non-linear predictor after a single initial calibration.

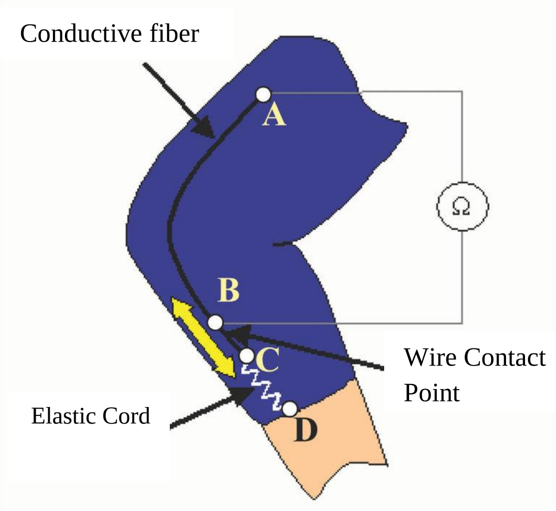

Figure 4: Knee monitoring using conductive fiber [27]

The last approach for knee monitoring device to be discussed in this section is based on acoustics sensor via air microphones [28]. Three different type acoustic sensors are applied; electret, MEMS and piezoelectric film. These devices were applied on a human subject, as he performed three cycles of seated, unloaded knee flexion/extension with two electret microphones positioned at the lateral side of the patella, one on the skin and one located 5 cm off the skin. In their study, the researchers concluded that practical implementation of contact microphones in a wearable device requires further interface noise reduction. The sensor placement in the knee area using this device is illustrated in Figure 5. For comparison purpose, the advantages and limitations of each knee monitoring devices that have been described here are summarized in Table 1.

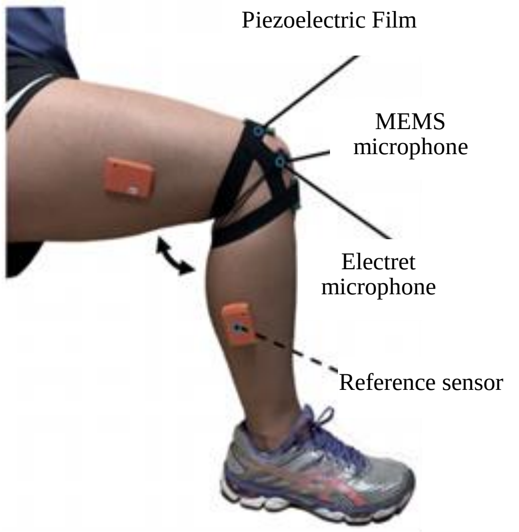

Figure 5: Knee monitoring using acoustic sensor [28]

III. Comparison of Different Type of Knee Monitoring Devices

Based on the discussion on several main examples of knee monitoring devices presented above, their respective advantages and constraints are presented in this section via a simple table form to allow direct comparison between each device. In addition to this, other related health monitoring devices for different human joints are also presented in the same table to allow diverse technology comparison. The comparison of the sensors' characteristics is presented in Table 1.

Table 1
List of Different Human Joint Angle Movement Sensors and Their Advantages/Limitations.

No	Human Joint	Type of Sensor	Parameter	Advantages / Limitations	Ref. No.
1	Knee	Electrogonio meter	Strain	Adv. – based on strain gauge application, straightforward measurement Lim. – high cost (hardware and software sold separately)	[19, 20]
2	Knee	Accelerometer, gyroscope	Velocity	Adv. – basic installation, low component cost Lim. – signal drift if not in motion	[22]
3	Shoulder, elbow	Inertial sensor	Angular rate	Adv. – basic installation, low component cost Lim. – signal drift if not in motion	[23]
4	Knee	Angular rate accelerometer, magnetometer	3D coordinate (via angular rate)	Adv. – reduce the problem with signal drift Lim – too many sensor elements, complicated circuit arrangement	[26]
5	Knee, hip	Conductive fiber	Electric conductivity	Adv. – small fiber is used, possible for wearable device Lim – difficult to identify multiple movement position along the conductive fiber	[27]
6	Knee	Acoustics sensor	Soundwave travel time	Adv. – wireless detection is possible, does not limit patient movement Lim – significant noise level (uncontrolled room condition)	[28]
7	Knee	Conductive wire	Electric conductivity	Adv. – simplicity of the measurement, low cost, and the sturdiness of the sensor Lim – use differential Wheatstone bridge circuit, so output signal is dependent on the temperature. Range of detection of up to 50 deg. only.	[29]
8	Fingers	Resistive bend sensor	Strain due to compression	Adv. – embedded into a glove, high resolution (0.1 deg.) Lim – require careful knitting work to place the sensor on the glove.	[30]
9	Fingers	Flexpoint bend sensor	Strain due to compression	Adv. – no moving parts, silent in operation, lightweight Lim – require associated components such as wireless board, data storage etc. (place in a box at arm position)	[31]
10	Knee (motion)	Piezoresistive sensor strips	Strain due to compression	Adv. – lightweight, fast response Lim – require extended circuit to record the movement (large size, difficult to attach to the body)	[32]

The list of critical concerns for each joint sensor in Table 1 can be summarized as follow:

a) Accelerometer / inertial sensor – drift issue when static
b) Electrogoniometer – high operational and maintenance cost.
c) Conductive fiber/wire – require to be attached to a flexible garment, not applicable for different body sizes
d) Acoustic sensor – prone to noise disturbance (error)
e) Resistive bend – require care to attach to the garment, or could damage the sensor.
f) Piezoresistive sensor – require bridge circuit (difficult to balance the offset), large circuit assembly.

As summarized above, there are still many improvements can be made to overcome the limitations of other knee monitoring devices. The application of plastic optical fiber for knee measurement offers several advantages including; small sensor component (due to relatively small in fiber diameter), low cost for sensor component assembly (using visible wavelength LED and photodiode) and less susceptible to noise when applied with appropriate filtering circuit. The problem with signal drift can also be eliminated via suitable intensity referencing method for optical fibers.

IV. Knee Monitoring Sensor based on Optical Fiber Bending Sensor: A Preliminary Result

In general, optical fiber sensor can be categorized based on its modulation techniques, such as the intensity-based, frequency-based and phase-based modulation techniques [16]. An intensity-based optical sensor is applied where the magnitude of light is being modified by the parameter of interest by initiating a loss in the light intensity (i.e. light attenuation). This technique requires the use of low-cost light sources and multimode fibre types together with simple optical components, rendering an economically low-cost system. Meanwhile, for phase and frequency modulations, they represent modulation approaches, in which the variable to be measured will cause a phase shift or frequency change of the coherent light wave. Opposite to the low-cost intensity modulation technique, these approaches are only possible through the use of a coherent light source, single mode fibre and a complex device for signal detection (e.g. interferometer), which are more expensive and complex.

The description on the sensor configuration aimed to be used for the knee monitoring application is presented in the following section.

A. Sensor Configuration under Investigation

Bending movement or sometimes knows as angular displacement can be measured using intensity modulation technique via the following approaches :

a) Longitudinal displacement – This method uses 1 input fiber and 1 output fiber.
b) Differential displacement – This method uses 1 input fiber and 2 output fiber.
c) Angular displacement – This method uses 1 input fiber and 1 output fiber as shown in Figure 6.

As far knee monitoring application is concerned, the longitudinal displacement (a) and the differential displacement (b) methods require further calibration steps in order to represent the angular movement in the form of linear displacement. The use of angular displacement method in (c) is straightforward and enable direct representation of the knee joint movement using optical fiber, thus being applied here. The sensor output estimation from the optical fiber sensor using this method is presented in the next section.

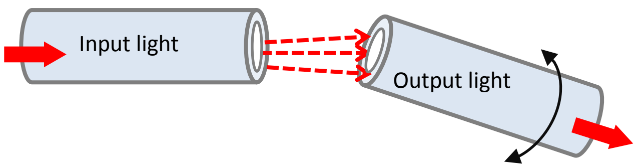

Figure 6: Light attenuation based on angular displacement fibers

B. Output Estimation Result

The output estimation for the optical fiber sensor configuration using the angular displacement method is obtained using the fiber loss equation [15]:

$$I_i(x,y,z) = \frac{A_i L_i L_0 I_0}{\pi \omega_i^2 (z_i)} \cdot \exp\left(-\Sigma_i\, n_i r_i\right) \cdot \exp\left\{-\frac{x_i^2 + y_i^2}{\omega_i^2 (z_i)}\right\} \quad (1)$$

Where:

*A*i is the i-th output fibre core area.
*L*i is the losses in the i-th output fibre.
L_0 is the losses in the input fibre.
I_0 is the light intensity at point (x, y, z) of the *i*-th output fibre.
$\exp(-\Sigma n_i r_i)$ is the additional losses parameters in the *i*-th output fibre caused by microbends.
a_o is the output fibre core radius.
ξ is the coefficient parameter of the light source.
θ_c is the fibre acceptance angle = sin-1 (NA/n_0).

The characteristics of output intensity level (brightness of the light) with respect to the different bending angle (degree) are presented in Figure 7. The objective is to investigate the maximum angular displacement (degree) that can be detected using this configuration. This is important to ensure that the studied technique can be applied to knee measurement application, which has a large range of motion that spine and respiration cases.

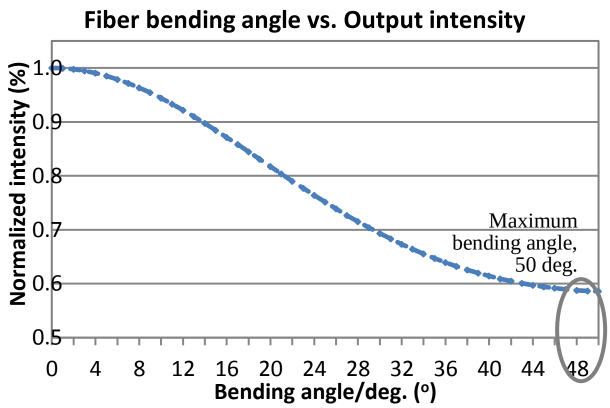

Figure 7: Output intensity variation with respect to joint angle movement

The variation of the light intensity output with respect to the detection angle (i.e. knee movement angle) is presented in Figure-7. The output intensity is presented in a normalized form, which ranged between 1.0 to 0.58 for bending angles (knee joint movement) between 0 deg. and 50 deg. The slope of the output in Figure 7 represents the sensor output resolution. From the graph, it is shown that flat slope towards higher bending angle (above 40 deg.) gives a poor sensor resolution at high bending angle. As the maximum knee movement is typically up to 140 deg. for the full range of motion (R.O.M.), the investigated technique in this study is not likely suitable for this application. Finally, another method is needed or at least some modifications to this technique are required to allow the detection of knee joint movement using an intensity-based optical fiber sensor.

V. CONCLUSION

A possible implementation of intensity modulated optical fiber bending sensor for knee monitoring application has been investigated, which technique has been previously applied for the detection of spine movement and respiration rate monitoring. For this study, the light intensity of the output fiber is estimated using the fiber loss equation, which results in the output intensity changes with respect to the imposed bending angle/angular displacement. From the calculated output, it was found that the maximum detectable angular displacement is only 50 deg., which is far lower than the typical rotation range for knee application. As a conclusion, the investigated technique requires further modifications to allow possible implementation of knee monitoring area. Several other types of knee joint monitoring devices have also been presented to highlight the contribution of other devices.

ACKNOWLEDGMENT

The authors wish to thank Universiti Malaysia Pahang for the financial support provided to carry out the study presented in this article under the grant no. RDU150364.

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