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# Review of Human Joint Monitoring Devices: Conventional vs. Optical Fibre based Sensors

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# Review of Human Joint Monitoring Devices: Conventional vs. Optical Fibre based Sensors

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**Abstract**. Health monitoring devices are highly demanded in order to determine patients' health condition, to monitor the health recovery progress, and to help the physiotherapist during rehabilitation period of a patient. This paper is focused on knee joint assessment devices and technology implementation. Knee joint angle measurement devices includes many devices such as accelerometer, electro-goniometer, torsiometer, acoustic, visual sensory, and optic fibre. There are several limitations to these technologies which require improvements. Many of the existing techniques and technologies are becoming conventional and there is a need to identify and to explore better methods to enhance the limitations of existing devices. The need of technologies with higher accuracy, reliability, and lower cost have always been a crucial factor. In this paper, a study of conventional and latest technologies are reviewed, and suggested to further explore the implementation of optical fibre based technology for the above-mentioned application. Optical fibre device has faster response, better accuracy, lighter in weight, lower cost, and is not effected by external physical variable such as electromagnetic waves as compared to conventional sensors.

## 1. Introduction
Health assessment devices for human is normally applied to different body areas such as blood circulation, heart rate monitoring, respiration assessment, gait monitoring, as well as lower and upper limbs motion detections [1]. Among all joint movements related to the lower limb motion, knee movement is considered the most important and critical part because of high exposure to injuries. Knee problems and injuries most often occur during sports or recreational activities, work-related tasks, or home projects.

Type of injuries among athletes are commonly related to strains and sprains [2]. The tough and aggressive force impacted on the knee joint during sport activities may incur problems in the tendons and ligaments that connects the knee structure which allow its mechanism to work smoothly [3]. Hence, these knee-related damages faced by athletes occurs to the tendons, ligaments, or meniscus. This will be followed by long period physical treatment, the possibility uses of drugs, or even surgical treatment. Nevertheless, there is a slight potential that most treatment results may not be able to heal the joint back to its original condition [4].

The aim of this research is to study various available techniques and technologies to assess the knee joint condition. There are many limitations to the current technologies which require improvements. Furthermore, many of the existing devices are becoming saturated in terms of improving the devices' weakness. Thus, there is a need to find and explore new methods, new sensors and new technologies which have not yet been applied in this field of research to overcome the limitations of existing devices. The need of technologies with higher accuracy, reliability, and lower cost have always been a crucial factor. Based on this research, it can be suggested that the technology need to be further explored and studied is based on light modulation or optical fibre techniques as it is faster in response, more accurate, lighter in weight, lower cost, and is not effected by external physical variables.

## 2. Knee Joint Epidemiology

A research conducted by Majewski in 2006 related to epidemiology study that was carried on 17,397 patients. He reported that injuries occurring to the menisci is the second highest among common injuries in the knee which ranges about 12% to 14%. Most cases of menisci injuries are from athletes who involved in soccer and skiing sports [5]. He added that injuries which frequently affect the knee is anterior cruciate ligament (ACL) with a percentage of 20.34%, followed by medial meniscus with 10.76%, and lateral meniscus with 3.66%. As observed during this study, patients that require arthroscopic treatments with ACL injuries are as high as 85%. A report by Nielsen [6] that ACL injuries and meniscus tears were 0.3 and 0.7 respectively per 1,000 patients in a year. Injuries associated with sports are only 27%, yet they were discovered twice as frequently among athletes than individuals harmed in nonathletic activities. Ruptures of the collateral ligament were found 4 times more common among athletes and ACL injuries were 7 times. Athletes showed less meniscus tears compared to individuals associated with nonathletic activities. Another report by Lohmander [7], teenagers involved in sports activities tend to have the highest rate of ACL tears. Annual incidence of ACL rupture reported by an in-hospital clinical diagnosis to be 30 per 100,000 in Denmark and 81 per 100,000 for ages between 10 to 64 in Sweden. Occurrence of symptomatic secluded meniscus tears is hard to find out. The beforehand cited in-doctor's facility examine detailed the yearly populace occurrence to be 70 for each 100 000 in Denmark. Majority of patients with an acute ACL injury are among people younger than 30 years [7].

Occurrence of multi-ligament knee injuries may be caused by both high momentum impact [8] such as car accident and low momentum impact such as soccer game [9]. Engebretsen *et. al.* reported in their research that from 85 patients with knee dislocation, 51% of them were high momentum impact injuries, and 47% were sports-related injuries [10]. In a survey of 303 patients with knee dislocations conducted by Moatshe *et. al*. [11], 50.3% of the knee dislocations were due to high momentum impact incidents and another 49.7% were due to low momentum impact incident. Miller *et. al*. also reported that obese individuals tend to get multi-ligaments knee injuries due to ultra-low velocity impact [12].

José Jair Alves Mendes Jr., published in year 2016 [13], in his study, he mentioned that there is a great demand for a device that is able to assess in generating a continues data analysis while the athlete performing his/her sport in their athletic environment instead of a lab. Knee condition during the recovering progress due to injuries is commonly monitored based on the range of motion of the knee movement. A limited range of motion (in degree angle) of the knee and irregular knee angle displacement could represent a poor condition of the knee [14]. It is reported that the knee joint is the most commonly injured joint for athletes or those who participates in athletics activities [15]. Post-surgical athletes may require to undergo extensive rehabilitation procedures before returning to pre-injury level, athlete's condition is observed based on pain and mobility limitation. Prior tests to assess knee joint conditions, athletes need to exhibit minimum criteria of active full range of motion, normal symmetric gait pattern, no joint effusion, and able to hop on a single leg without experiencing pain [16]. Knee extension reduction of $3^o$ is associated with poor post-surgical outcome [16]. Asymmetries in the knee range of motion also indicates degenerative changes toward knee joint [17, 18].

## 3. Main Requirement for Human Joint Monitoring Devices

The main objective of conducting this research is to investigate the possibility of developing a low-cost portable measurement device for the knee movement which can provide continuous measurement data. Device used to assess knee joint range of motion is mainly goniometer as it is the common device used to measure joint angles. It can be easily used and obtained at low cost, but angular reading may vary due to manual application of the device. Another issue is lack of consistency due to human error and it can only assess in providing static reading. Other latest technology devices for the same application uses electro-goniometer, accelerometer, and gyroscope. These sensors are able to provide results with better accuracy and continues results in dynamical condition [13, 19, 20]. However, the use of these sensors incur high cost, complexity in the device assembly, requires a professional person to handle it, experience the patient discomfort due to the weight or size of the device, the wiring connections caused discomfort for the wearer, and it also may lack of accuracy caused by the noise in the electronic signals, or time delay when generating the data.

In certain knee monitoring application, there is a need to have a device which is immune to electromagnetic interference so that the results from the applied device is valid and reliable. Optical fibre sensor is inherently immune to this kind of excessive environment for monitoring condition, lighter in weight, available at cheaper cost, and hypothetically it has a higher accuracy due to the unnoticeable time delay in the analog signal interface with the detection sensor. For the optical sensors, light will be the variable signal/parameter instead of force or acceleration for other devices.

## 4. Recent Publications in Human Health Monitoring Applications

Several researches, especially articles from the last 10 years of publications have been reviewed to obtain general ideas on suitable approaches to assess human joints angle range of motion, to study the advantages and limitations of each methods, and to determine which parameters are best used to achieve the most satisfactory result for knee joint angle measurement assessment.

A survey conducted in 2008 by Zhou *et. al.* on existing technologies for human motion tracking during rehabilitation. The researcher reviewed sensor related technologies such as inertial sensor, magnetic sensor, and acoustic based systems. In addition, they also reviewed visual tracking systems in 2D and 3D, and several robot-aided tracking systems. It was concluded in the end that there were a few issues need to be improved and solved. It was also highlighted, some significant device properties need to be provided by the device which are wireless data transfer, improved accuracy, friendly interface, portable device, and real time operation/ continues data transmission [21].

Another review was conducted by Roriz *et. al.* in year 2014 studying conventional sensors and other related techniques until latest approaches available at that time. A comparison was made among the sensors for the application of human biomechanics rehabilitation. It was concluded that fibre optic is considered advantageous compared to other sensors in the medical and biomechanical fields as they are smaller, easy to implement, minimally invasive or can be non-invasive, has lower risk of infection, highly accurate, well correlated, low cost, and multi-plexable [28].

Determining joints angle has always been very important to assist in finding solutions and solve problems related to humans' biomechanics. There is always a need to improve the joint angle measurement systems. The following paragraphs discuss in details several sensing mechanisms applicable for human joint measurement based on literature study of previous articles.

### *4.1 Stress & Strain Parameters Approach*

An attachable clothing sensor system was developed by Bergmann *et. al.* to measure knee joint angle in 2013. The flexible sensor is integrated within the clothes to measure daily knee movement of the human volunteers. The sensor is aimed to be applied for clinical purposes for patients who need self-performance monitoring. The sensor illustration is as shown in Figure 1 [27].

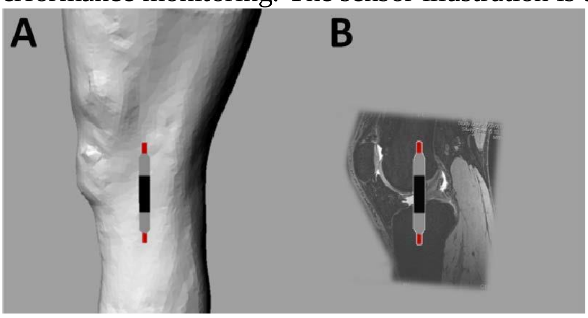


**Figure 1.** Attachable Clothing Sensor [27]

**Figure 2.** Elastic sensor embedded in a kneepad [29]

Results shows that the comparison yielded an average root mean square error of 1 deg. (estimated) between the knee angular reading of the reference system and the developed system. Whereas, the mean absolute error is 3 deg. [27]. In 2014, a novel low cost sensor for knee angle flexion measurement was developed and evaluated. The system is based on the use of elastic sensor embedded in a kneepad, it is as shown in Figure 2 [29]. Results showed that the knee angle measurement range is from 0 to 120 degree, the mean range is 5.82° ± 1.93 (repeatability), root mean square is 1.28 degree (accuracy), and correlation of coefficient of 0.80 - 0.91 (reliability) [29].

*4.2 Using Resistance Parameter Approach*

Another approach was conducted in 2011 by Kramer *et. al.*, using a curvature sensor composed of a thin, transparent elastomer film embedded with a microchannel of conductive and a sensing element. The authors claimed that the device was the first use of liquid-embedded elastomer electronics to monitor human or robotic joints angle. The working principle combines stretch, pressure, and curvature sensing criteria to derive and detect bending and joint position. The device as shown in Figure 3 [24].

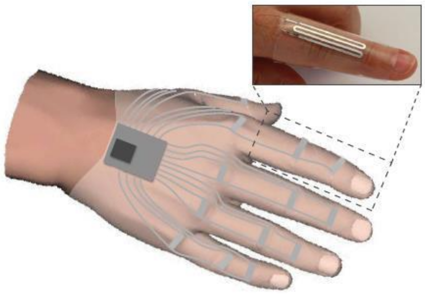

**Figure 3.** Curvature sensor [24]

Curvature detection is obtained by estimating the difference in resistance for the applied material. Difference in resistance is taken from actual resistance measured at that time and then the resistance is estimated by mathematical approach. From the study [24], the measuring angles range goes from 0 - 100 degrees, whereas measurement error can deviate up to 20.87%.

In 2017, Kim *et. al.* published an article on finger muscular forces analysis using exoskeleton system. The developed system aimed to measure the puling force and joint angles of the fingers. Hence, in order to measure the joint angle, potentiometer was used and the root mean square error of the angle reading was 1.1642°. The illustration of developed system is as shown in Figure 4 [32].

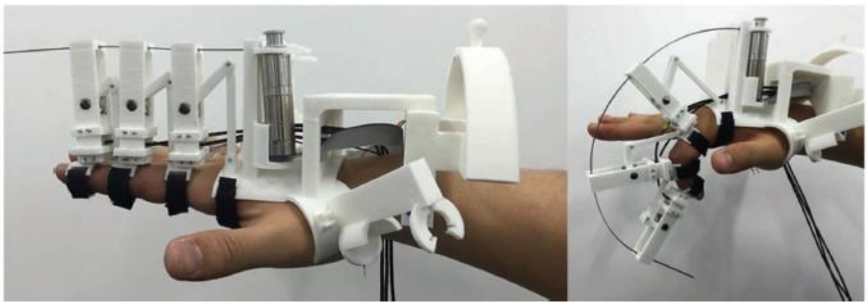

**Figure 4.** Finger muscular forces analysis using exoskeleton system [32]

In 2018, Saggio *et. al.* conducted a study on flex sensor application in biomedical devices, especially for the posture and motion capture applications. The study focused on determining the dimensions and geometrical designs to improve linearity and accuracy of the sensor. In their design, resistance behaviour of the flex sensor was used to determine the bending angle. The suitable measured angle for this device is in the range of 0 - 120 degrees. It was concluded that for small joints applications, problems of non-linearity and low sensitivity raised. However, this problem can be solved with better optimized geometrical design [33].

*4.3 Using Position, Velocity, and Direction Parameters Approach*

In the year 2011, Bakhshi *et. al.* carried out a study on a body joint angle measurement system, developed using IMU sensor. In this research, it presented an approach to measure and monitor body joint angles using inertial sensor. The device was attached at two locations along the leg as shown in Figure 5 [25]. A motion capture system was utilized as a reference to compare the IMU system's accuracy. The system results showed that the range of error varied from 0.08 - 3.06 degrees [25].

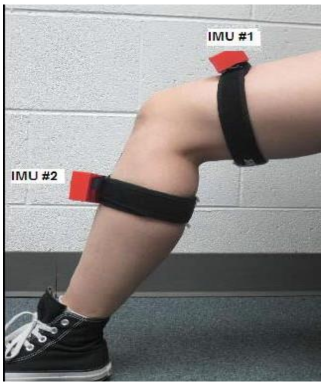


**Figure 5.** IMU sensor implementation [25]

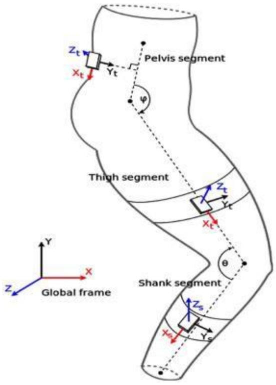


**Figure 6.** Wearable inertial sensor implementation [31]

A continuous movement detection device using wearable inertial sensor (accelerometer) was developed in 2015 by Ahmadi *et. al.* to monitor athletes' movements during sport training session. The sensing mechanism of the device was by measuring the acceleration of each different sensor which provides enough data to draw a curve and then to measure the angle between the position of each sensor located at the pelvic area, thigh, and shank as shown in Figure 6. Results also had shown of accuracy up to 98% [31].

*4.4 Using Light Parameter Approach*

A different method was proposed by Donno *et. al.* in 2008. They used optical fibre goniometer for dynamic angular measurements which was aimed to be applied to human joint movement monitoring. The working principle of the sensor is as shown in the Figure 7 [22]. The developed prototype sensor has a range of angle of 90 deg., a resolution of 0.01 deg. and standard deviation of 0.1. The advantages of this developed prototype were light weight, flexible, high response, and high accuracy.

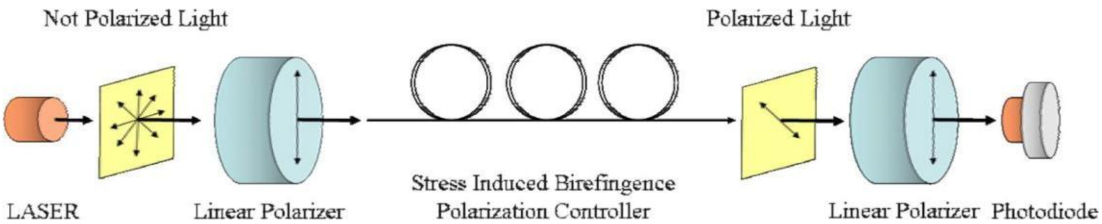


**Figure 7.** Optical fibre goniometer working principle [22]

In 2011, a fibre Bragg grating in PVC foils sensory method was developed by Rocha *et. al.* for knee joint movement monitoring during rehabilitation process. The proposed system is based on single optic fibre Bragg grating with resonance wavelength of 1547.76nm. The developed device was aimed to assist physiotherapist to measure, record, and evaluate patient's condition with bone, muscular, and joint problems for athletes. As shown in Figure 8 [23], the device was able to provide results of light waveform against time. Other information on range of angle of the knee, sensor accuracy and precision are also unknown. This device has the potential to be improved, it is also considered light in weight, low cost, not effected by electromagnetic interferences.

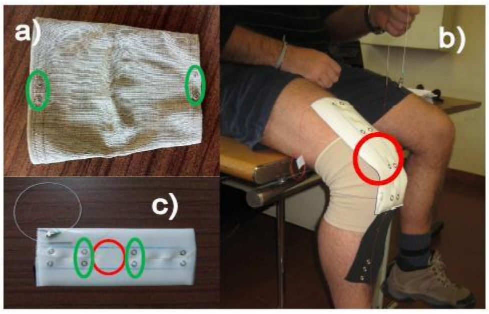


**Figure 8.** Fibre Bragg grating in PVC foils [23]

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An alternative of human joint movement using optical-based sensor was tested using a fibre optic curvature sensor in 2012 by Stupar *et. al.* A low cost plastic optical fibre was used is the setup and the measurement is done based on light intensity modulation. This sensor is simple, light, flexible, and immune to electromagnetic interferences. The device illustration is as shown in Figure 9 [26]. Range of detection can reach up to 120 degree, and the results showed that the standard deviation is 0.18 degree. A few limitations of this device are not suitable for application range from 0 - 25 degree due to its low sensitivity (narrow range), and when measuring an angle of up to 140 degree and above, the fibre physical structure will be weakened and may crack [26].

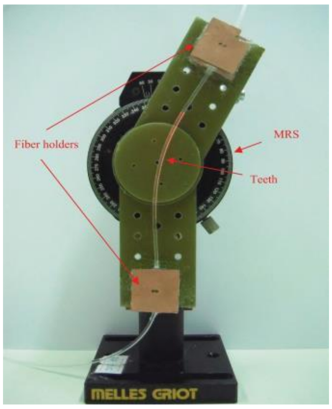

**Figure 9.** Fibre optic curvature sensor [26]

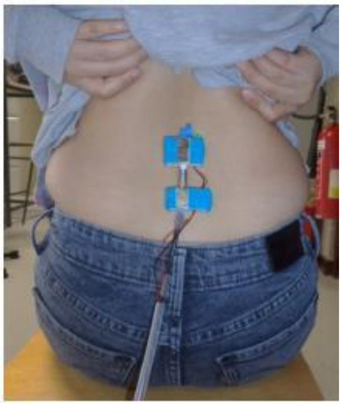
**Figure 10.** Fibre optic sensor using intensity modulation for spine monitoring [30]

In 2015, another application of optical fibre sensor for spine bending angle measurement was carried out. The measurement concept of the angle is based on light intensity modulation, where one input fibre and three output fibres were simultaneously used to provide the bending angle of the spine based on fibre tilt angle loss measurement. The results from this device was a range of detection between -22 to 22 degree (front-back and left-right sides) with an average sensitivity of 0.05 degree [30].

Another publication took place in 2018 which is focusing the development of body posture (at wrist and elbow) monitoring device using fibre Bragg grating and flex sensors. The maximum measured angle can reach up to 60 degree [34]. In addition to this device, another fibre Bragg grating goniometer was introduced in 2018 for the application of elbow and ankle joints. The approach used the conversion of rotational movement of joint into strain variation and then derive the angle by a mathematical equation. The device illustration is as shown in Figure 11. This device can measure between a range of 0 - 200 degree with a resolution of 0.06 degree [35].

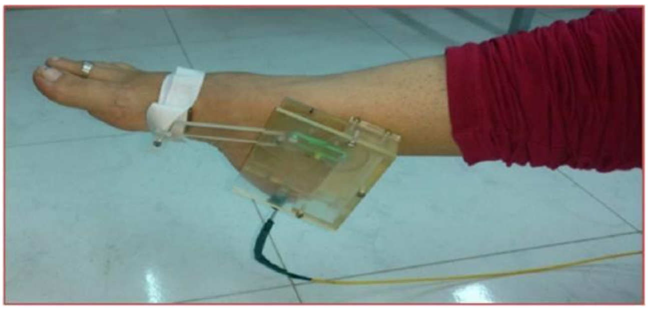
**Figure 11.** Fibre Bragg grating goniometer [35]

## 5.0 Performance comparison of different human monitoring devices

A conclusive table is presented to illustrate the gathered data which can be categorised in its respective publication year, area of the research, type of sensor used, parameter of sensory mechanism, advantages and limitations of each system, as shown in Table 1.

**Table 1.** Summary of Human Joint Monitoring Devices Comparison using different Sensors

| No | Year | Human Joint | Type of Sensor | Parameter | Angle Range (Degree) | Advantages (+) / Limitations (–) | Ref. [No.] |
|---|---|---|---|---|---|---|---|
| 1 | 2008 | General use for human body joints | Optical fibre goniometer | Polarized light | 0 - 90 | + Light weight, flexible, fast response, and high accuracy.<br>– Only measures between 0 -90 degree. | [22] |
| 2 | 2011 | Knee | Fibre bragg grating | Light waveform | N/A | + Light weight, low cost, immune to electromagnetic interference.<br>– Data is not transformed into angle measurement, but is in wavelength form.<br>– Accuracy and precision is unknown. | [23] |
| 3 | 2011 | Hand, fingers | Curvature sensor | Strain & Pressure | 0 - 100 | + It is new concept, light weight, and simple.<br>– Measuring range s between 0-100 degrees only.<br>– Error can deviate up to 20.87%. | [24] |
| 4 | 2011 | Knee | IMU sensor | Position, Direction & velocity | 0 - 130 | + Applicable for various joints.<br>– High range of error variation | [25] |
| 5 | 2012 | Knee | Fibre optic curvature sensor | Light intensity modulation | 0 - 120 | + Low cost, simple, light weight, flexible, immune to electromagnetic interference, and high accuracy.<br>– Limited range of angle measurement.<br>– Cable may crack or spoil due to design limitations. | [26] |
| 6 | 2013 | Knee | Flexible sensor | Stress & Strain | 0 - 90 | + Light weight, small, and simple.<br>– Less practical, and high error. | [27] |
| 7 | 2014 | Knee | Elastic sensor | Stress & Strain | 0 - 120 | + Able to measure up to 0-120 degrees.<br>– Low accuracy. | [29] |
| 8 | 2015 | Spine | Optical fibre bending sensor | Light intensity | -22 to 22 | + High accuracy, light weight, immune to electromagnetic interference.<br>+ Sensitivity of 0.05 degree<br>– Low range of angle measurement. | [30] |
| 9 | 2015 | Pelvic, knee | Inertial sensor | Velocity & direction | 0 - 70 | + Good accuracy, and good amount of data provided.<br>– Bulky, and uncomfortable to wearer. | [31] |
| 10 | 2017 | Hand finger | Potentiometer | Resistance | 0 - 90 | + Able to measure angle and puling force of the finger joint.<br>– Bulky, and uncomfortable for user. | [32] |
| 11 | 2018 | Small joints | Flex sensor | Resistance | 0 - 120 | + Able to measure between 0-120 degrees.<br>– Non- linearity in results, and low sensitivity. | [33] |
| 12 | 2018 | Wrist and elbow | Fibre Bragg grating | Light wavelength & resistance | 0 - 60 | + Used for wrist and elbow.<br>– Low range of measurement, between 0-60 degrees only. | [34] |
| 13 | 2018 | Elbow and ankle | Fibre Bragg grating goniometer | Light wavelength | 0 - 200 | + Used for elbow and ankle, wide measuring range between 0-200 degrees, and has high accuracy.<br>– Design needs improvement to be made with less wiring, and more user friendly. | [35] |

## 6. Discussion and Summary

Based on summarized information provided in Table 1, it can be concluded that the application of conventional sensors for human health monitoring applications such as accelerometer and potentiometer has the problem of being bulky, uncomfortable for the wearer, and low accuracy because the obtained results are based on estimation algorithm which depends on direction, velocity, and position. Moreover, the measurement does not translate the obtained results directly from the moving joint meant to be measured. Overcoming these limitations have been a challenge as the demanded device needs to carry the criteria. These significant elements are lightweight device for users' comfort, low in overall device cost for general healthcare centres, device must be able to measure full range of joint motion, and it should give reliable accuracy. Researchers have suggested the use of light related applications such as optic fibre concept due to its light weight, lower cost, and by having the light beam as the transmitted signal, it may produce a result with better accuracy due to the fast signal transmission and response at the very minimal range of movement. In medical fields, the implementation of lasers and optical fibre based technologies is now becoming the replacement of most conventional tools. Thus, there is a significant demand to apply this technology in knee, fingers, elbow, spine, shoulder and wrist applications. Furthermore, as can be observed from Table 1, applications which uses light intensity or other associated light parameters (frequency and wavelength) does improve measurement accuracy. Nevertheless, optical-based devices have the limitation of being able to measure a very limited range of movement due to challenge of transforming the light waveform movement or bending and translate it into joint range of movement. This is because some techniques may cause the optical fibre / cable to break when bent or may result in the light signal to scatter in wide angle range. Hence, it is suggested for researchers to focus on light and optical fibre related methods as they have many advantages compared conventional sensors. Still, there is a need to improve the working mechanism design to be able to build a device with better accuracy, practicality, reliability, and able to measure the joint full range of motion.

Upon accomplishing this comparison study, it is highlighted that the grow rate of the research in health monitoring areas are increasing. Most researchers are mainly exploring and heading toward optic fibre and laser related technologies to achieve better device performance. It is also concluded that optic fibre related technologies still need some improvements in the method of implementation to achieve better results. The authors believe that the implementation of optic fibre technology has a great potential in various applications related to human health monitoring due to their advantageous compared to existing conventional devices.

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