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Knee Flexion/Extension Measurement System using Wearable Sensor

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Abstract: Knee Osteoarthritis is a complex disease influence by various aspects, containing aging, wear and tear and the loading environment. Examining biomechanics of a knee during walking is particularly relevant and clinically important because of the walking is most important cyclic and load-bearing activity. A unique and cost-effective knee angle measurement system by employing a wearable sensor is proposed to compute knee joint angle. This knee angle measurement system is valuable to doctors and health center for diagnostic and rehabilitation purposes. This project presents a portable and lightweight knee joint angle measurement system allowing effortless donning and doffing by means of the wearable sensor. A body mount knee joint angle measurement scheme that makes use of a flex sensor which acts as a flex/bend sensing resistor. The knee flexion/extension measurement scheme mainly made up of two parts: one is knee support with Flex sensor and hardware assembly and the second part is combination of signal processing and wireless communication. The system has used Flex sensitive resistor to sense a flex/bend of knee during walking. Joint angles are computed at Flex sensor and hardware assembly unit in instantaneous by monitoring of knee angle. The proposed scheme is easy to use and can be used in clinic or unsupervised environments for knee joint angle computation. Knee angles are informative data in the evaluation of biomechanical function of the people as well as of patient affected by osteoarthritis, stroke and Parkinson's disease.

Keywords — Flex sensor, Knee biomechanics, Knee joint angle measurement system, Real-time monitoring, Wearable module, Wireless communication

I. Introduction

The knee is one of the most complex and largest joint of our body. The knee joins the femur (thigh bone) to the tibia (shin bone) of leg. There is an interest in wearable sensor technology increased in last many years as an apparatus for rehabilitation application in community or home environment. Nowadays, the studies have focused on assessment of inertial measurement unit as sensor that provides merely indirect measures of joint motion. It is more direct to measure knee joint kinematics by means of wearable and flexible sensor [1]. The purpose of this study is to design and experiment a wearable system using flex sensor, for measurement of dynamic knee angles for the duration of everyday activities and gait. The technology of wearable sensor presents a potential solution to this barricade by enabling functional outcome to be calculated outside the clinic or laboratories. Osteoarthritis is very common type of the arthritis and it is frequently influences the knee. The knee joint angle measurement is a significant facet of body movement analysis because of this information is useful to understand movement disorders as like arthritis. The knee joint movement data could aid medical diagnosis and treatment.

At a dedicated gait laboratory, most of the researches on knee joint biomechanics and kinematics have been carried out. Although this procedure provides detailed information, it is time-consuming and expensive, subject required to be brought to the laboratory. A body mounted system that made up of wireless module and sensor network, which should be easy to put it on and might be used in clinic or taken out into the community. It provides capable technique to collect clinically important data regarding knee function during daily activities. Technology of wearable sensors offers a possible solution to this barricade by enabling function outcome to be measured outside the laboratory or health centre. The measuring system must be able to measure joint flexion/extension of the knee accurately and can be used potentially in the future to diagnose and manage Osteoarthritis. The development of flexible sensor that can be integrated into clothing to assess knee motion is as emerging and revolutionary concept [1].

The technique has developed and implemented for gait analysis and measuring knee joint angle using Gyroscope sensor. By using of Gyroscope sensors, requirement of cameras has been eliminated and therefore cost of whole setup has considerably reduced. A gyro was interfaced with

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microcontroller to collect data and the collected data sent to the computer for graphical representation [2]. The knee joint angle measurement scheme was also designed using knee brace slider crank assembly and signal processing unit [4]. The accelerometer-based measuring system was developed using device called BioStamp RC [6]. The system using tri-axial accelerometers were examined to compute knees' angle, displacement, velocity and acceleration [5]. The system was developed by interfacing flexible conductive polymer element and wireless node for data acquisition [7]. Wearable system using Ultra Wide Band transceivers developed to calculate the knee flexion/extension angle as it is clinically important parameter [8]. Magnetic Angular Rate and Gyroscope (MARG) sensor analogous to IMU but include magnetometer was used for execution and verification of a knee monitoring system [9]. The challenge is a computational problem for calculating the angle while making use of accelerometer, gyroscopes and MARG sensor. The output of gyroscopes effected by offset errors since a gyroscopes offer rate of rotation. It is needed of integration of its output to find out the rotation amount of an object. These systems compute knee angles with precision equivalent to motion analysis scheme but unsuitable for real-time monitoring and long-standing application since it was requirement of subject to put on many integrated sensors placed at correct location with the help of wire or wireless module. Moreover, algorithms of signal processing were complex of these systems and they need to filter the primary signal for further process. As a result, complexity of the system increased with rising amount of the sensors and so as system has been more complex.

Although, these sensor-based techniques had been explored in different research setups but could not get many opportunities of commercialization or to be used in common purpose and medical association. The objective of this study is focused on computing knee angle (flexion/extension) of personnel in any surroundings.

II. RELATED WORK

Bergmann et al. [1] presented the design for a flexible clothing sensor system that was able to use for evaluation of knee motion which was patient centered development process. A carbon composite was used as the base substance to design the flexible sensor. A Wheatstone bridge arrangement had been used to compute the resistance variations as attachable clothing sensor. The output of the computing circuit was connected to an analog input pin of the microcontroller board and was collected via a Simulink model with 50Hz sampling frequency. Bhosale et al [2] studied the technique which was focused computing the various gait parameters by means of gyro sensors. By mounting 3 gyro sensors at ankle, knee and hip of a leg and data were acquired from those gyro sensors. The output of Gyro sensors transported to MSP430 using I2C communication protocol. Data were processed by microcontroller and display the data in graphical format by a computer terminal. The monitoring system of Kim et al. [3] of posture analysis measures the knee joint angle using potentiometer and then transmits the data to a Smartphone through Bluetooth communication. The Smartphone application with dynamic and static posture classification algorithm can be used to monitor the user's posture in real time and for future analysis by storing data.

Sigh et al. [4] observed unique and inexpensive measurement system which was made up of force sensitive resistor to compute the knee joint angle. This system mainly contained of knee brace with slider crank assembly, signal processing module and wireless communication system for data transmission. The measurement system used Force sensitive resistor to sense the force applied on knee while walking. Four bar slider crank arrangement was used to convert the circular motion into reciprocating linear motion. Knee angles were calculated at a signal processing unit in instantaneous by real-time monitoring of the movement of subject. Nwaizu et al. [5] developed a system based on an accelerometer to calculate velocity, movement angle, acceleration and displacement for the knee. The system used two tri-axial accelerometer boards that were connected to the Arduino Mega microcontroller board. The microcontroller board was connected to a computer by use of USB. This board covers analog signal acquired from the accelerometers into the digital signal for further computer processing as like display and storage. To validate the measured knee angles by the accelerometers, a flexible goniometer was used to calculate the actual angles from the knee model. McGinnis et al. [6] proposed a system which was skin mounted and based on an accelerator to measure knee angles and range of motion that was easy to apply on patient. Two BioStampRC devices were used to access accuracy of an accelerometer-based system to calculate knee angles and Range of Motion (ROM) during the static posture test of knee flexion/extension. BioStampRC Investigator App was used to configure a study, view and download data and upload data to the MC10 Cloud Computing Infrastructure for further processing and investing. The ROM of knee and knee angles were calculated by defining two anatomical calibrations. These calibrations were specified by the two direction cosine matrices, RT for thigh and RS for the shank.

The system developed by Papi et al. [7] consisted of a flexible conductive polymer unit integrated with data acquisition mode. The data acquired through wireless communication through this node which can be fixed on the knee over the leggings. Data were gathered from the flexible sensor attached with leggings and gold standard 10 camera motion capture system simultaneously. The correlation between signal of sensor and reference angle of knee flexion was defined for each subject to allow the

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conversion of the voltage output into degree of angle. The knee angle calculated through the sensor and reference system were compared using absolute error, root mean square error, Bland-Altman plots to evaluate accuracy and reliability of the system for test-retest. Qi et al. [8] designed a measurement system by use of Ultra-wideband transceivers to compute the knee flexion/extension angle. A pair of antennas was very small and light that specially designed for Ultra-wideband application placed on the adjoining segments of a knee joint. The Time of Arrival (TOA) estimator was used to acquire the range data among two antennas. The correlation-based technique was used to estimate the Time of Arrival of the first received pulse at the receiver. The measured distance was further used to calculate the knee flexion/extension angle by means of the cosine law. Bloomfield et al. [9] studied an execution and verification of knee monitoring to compute knee joint data in various degrees of freedom. The system was easily configurable and no frame-alignment calibration procedure was needed for measurement after visually placing/replacing sensors on patient. A quaternion attitude estimation based method of extracting the knee angles from independent wearable sensors was used to develop a mobile software system. The system used MARG sensor, and it was validated by use of a robot phantom and comparing the result with a gold standard motion capture system.

III. Methodology for Knee Angle Measurement System

Knee angle measurement system mainly categorized into three parts – Sensor, Data communication and Display.

1. Sensor: Flexible sensor is used to calculate knee angle during walking and other static postures like standing and sitting on a chair. It coverts knee angle into resistance value

2. Data communication: Microcontroller converts analog input from sensor into digital form and output at digital pin is transmitted to Bluetooth module. Bluetooth module is used to establish wireless communication between microcontroller and laptop/Smartphone.

3. Display: Real-time data are received and can be displayed in receiver system. Smartphone or laptop can be used as receiver module.

A. Knee Support with Hardware Assembly using Flex Sensitivity Resistor as a Sensor

For measurement and real-time monitoring of knee flexion/extension, it is a requirement for a sensor that is light-weight and can be fitted effortlessly as well as very simple to donning and doffing. Also, a person should wear it without any support of help and sensor must be competent for long term monitoring application without any constraint. Flex sensor has used to sense the flex/bend variation during walking and it converts flexion/extension of knee into resistance. A flex sensor also called bend sensor that calculates the amount of deflection or bending of it. The flex sensor used for a knee angle measurement system is shown in Fig. 1. Generally, the sensor should be fixed to the plane and resistance element of sensor is varied by bending/flexing the plane. The resistance of a sensor is directly proportional to the amount of bend and therefore it can be used as goniometer, hence it is frequently called a flexible potentiometer.

Polymer ink was printed on one side of the flex sensor and this ink has conductive particles implanted in it. The conductive particles give the ink resistance according to bend/flex of sensor. Through combination of the flex sensor with a static resistor to construct a voltage divider, it could be able to produce a variable voltage that can be converted into angles using microcontroller's analog-to-digital converter. Flex sensors should be used in extensive areas of studies and from computer interfaces, treatment, security systems and music interfaces too.

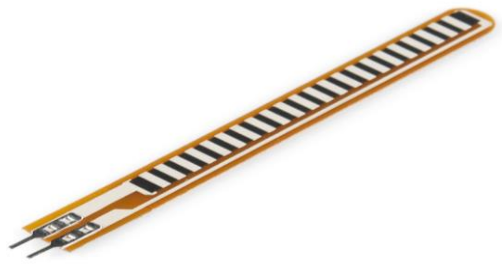

Fig. 1. Flex sensor

Knee supports have been used to attach Flex sensor and remaining hardware circuitry. Therefore it can be made wearable sensor module which also support to knee joint. The knee support should be used in combination with a rehabilitation program that includes strength training, flexibility, modification of activity and technique refinement. The knee support patella (pair) used in project on which measurement hardware system is attached. Knee support is manufactured using 75% closed cell Neoprene cell which is most durable fabric and 25% stretch nylon, allowing for the knee to experience maximum compression. Because of stretchable fabric, it is comfortable and can be easily fit to variety of people.

B. Knee Angle Measurement System

The Knee angle measurement system made up of mainly two components: i) knee support with flex sensor assembly and ii) signal processing part accompanying of wireless communication. Flex sensor has used to sense the flex/bend variation throughout walking and it converts flexion of knee into resistance. A variation of knee joint angles is calculated by means of microcontroller in real time via on-line supervising of knee angle. The Bluetooth module used to achieve communication between transmitter and receiver

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module through wireless communication. Block diagram for proposed measurement system for monitoring and measurement of knee angle is shown in Fig. 2. Flex sensor converts variation in flexion/extension of sensor into appropriate resistance value which can be further processed to measure knee angle. Voltage divider configuration is employed to compute the resistance deviations of the flex sensor. A voltage source applies across a series of two resistors R1 and R2. The voltage drop across R2 (nearby to ground) is called Vout, which is the divided voltage of devised circuit exists to make. The voltage divider equation assumes that the input voltage (Vin) and resistor values of both resistor (R1 and R2) of the devised circuit are known. Given those three values, the output voltage (Vout) can be found by using equation 1.

$$Vout = Vin * \frac{R2}{R1+R2} \quad (1)$$

The output from the voltage divider was connected to an analog input pin of the data acquisition board. Arduino Nano- microcotroller board based on Atmega328p has been used for data acquisition. The Fig. 3 shows schematic of hardware assembly board. In this schematic, R1 is fixed resistor along with R2 as a Flex sensor used for voltage divider configuration.

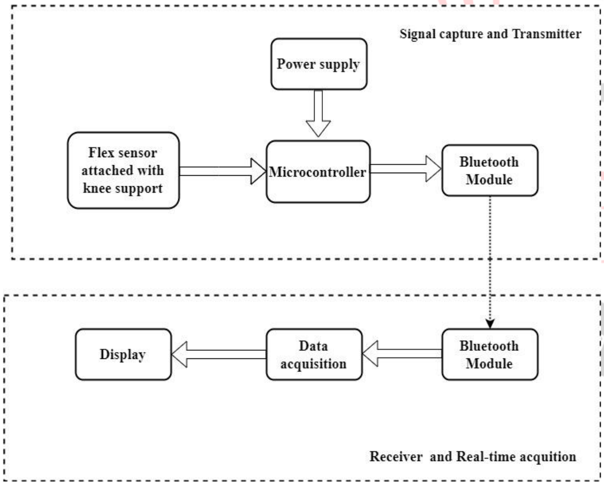

Fig. 2. Block diagram of knee angle measurement system

Data acquired on analog pin are processed and converted into digital form in microcontroller board. The Atmega328p based microcontroller communicates with Bluetooth module using serial port (USART). Bluetooth module HC-05 is used for wireless communication between microcontroller and display device which may be Smartphone or Laptop. Real-time data of knee flexion/extension acquired on Smartphone. The hardware platform employing Flex sensor is powered through battery.

C. Hardware Integration

After completing all the steps of PCB making like design schematic layout, layout print on PCB, etching, cleaning and drilling, all the hardware components should be solder on circuit board. For easiness and flexibility point of view, appropriate pin headers are soldered, so that components can be connected and detached easily. In this way Arduino Nano board, Bluetooth module and Flex sensor are easily detachable from the circuit board. The device is connected at one end of battery connector and plugs the battery clip onto a standard 9V battery. Final hardware assembly integrated all components shown in Fig. 4. This hardware assembly will be mounted on knee support for monitoring and measurement of knee angle.

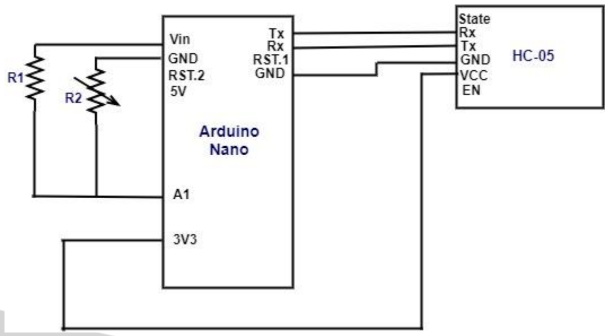

Fig. 3. Circuit interface of measurement system

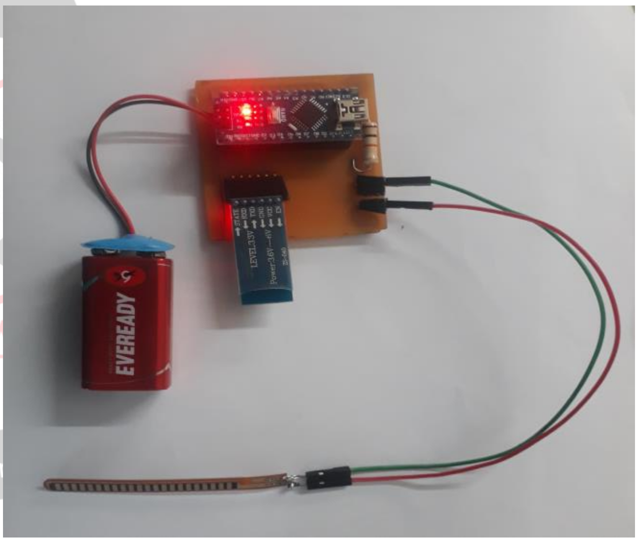

Fig. 4. Hardware assembly

Hardware assembly having microcontroller and Bluetooth module is integrated with Flex sensor and then whole system has mounted on Knee support. The measurement system should be fixed on the knee support in that way, a flex sensor will be placed on lateral side of leg when this system will be worn by subject/person. The proposed wearable system for knee flexion/extension measurement is geared up for execution. The knee angle measurement system should be worn by subject on knee as like normal knee support. Fig. 5 shows knee joint angle measurement system tied on the knee. Make enable Bluetooth of Smartphone and pair it with Bluetooth terminal of measurement system. Then instructions are given to subject for walking in defined area for experiment. Real-time data has started to be displayed in mobile screed

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in the value of knee angle while he/she is walking.

Fig. 5. Knee Flexion/Extension measurement system tied on the knee

IV. Result and Discussion

In this paper, wearable knee angle measurement system using Flex sensor for real-time monitoring has been proposed. The instruction is given to make flexion/extension of knee while sitting on chair. The variation of knee angle while doing knee flexion/extension has been plotted on graph. The resulted graph is shown in Fig.6. While subject keeps leg straight, it considers knee angle 0 degree and bending of knee while sitting on chair, knee angle becomes approximately 90 degree. The accuracy of the result depends mainly upon positioning of a Flex sensor. Flex sensor has fixed on knee support in such way; it will be positioned on lateral side of leg. In experiment, it has been observed the obtained result is accurate and have maximum tolerance of only ±10degree. The result can be obtained as plotted graph while real-time data are acquired on laptop. In other way, real-time knee angle acquisition has done on Smartphone display in digital form. The log file from Smartphone can be shared to doctor or clinic through mailing/messaging option for investigation or observation.

Measurement of knee angle has done during walking also in this experiment. The real-time data are acquired on Smartphone display in digital form. The obtained data on display of Smartphone are shown in Fig. 7. The log files of obtained result which can be shared by Smartphone shown in Fig. 8. Knee angles have measured while sitting on chair and walking. The obtained result can be summarized as table 1.

Table 1 Measured knee Flexion/extension angles

Different Postures	Measured Knee Angles	
	Knee Angles in Degree	***Tolerance in Degree***
Knee Extension (Straight leg)	0	±5
Sitting on Chair (Knee flexion)	90	±5
Walking	4 - 46	±5

We have proposed and experimented light weight, portable and cost effective knee joint angle measurement system for the purpose of real-time monitoring of knee angle. The benefits of this system over other systems lie in less complex signal processing, easy and comfortable donning and doffing.

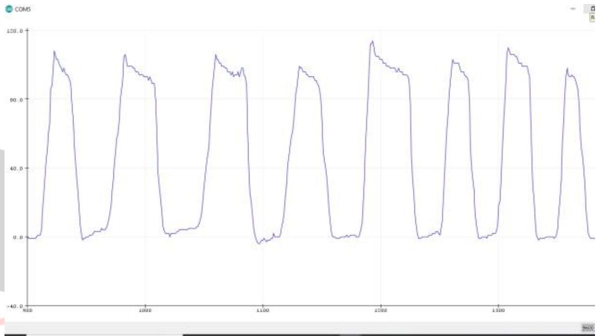

Fig. 6. Graph of Knee flexion/extension angle

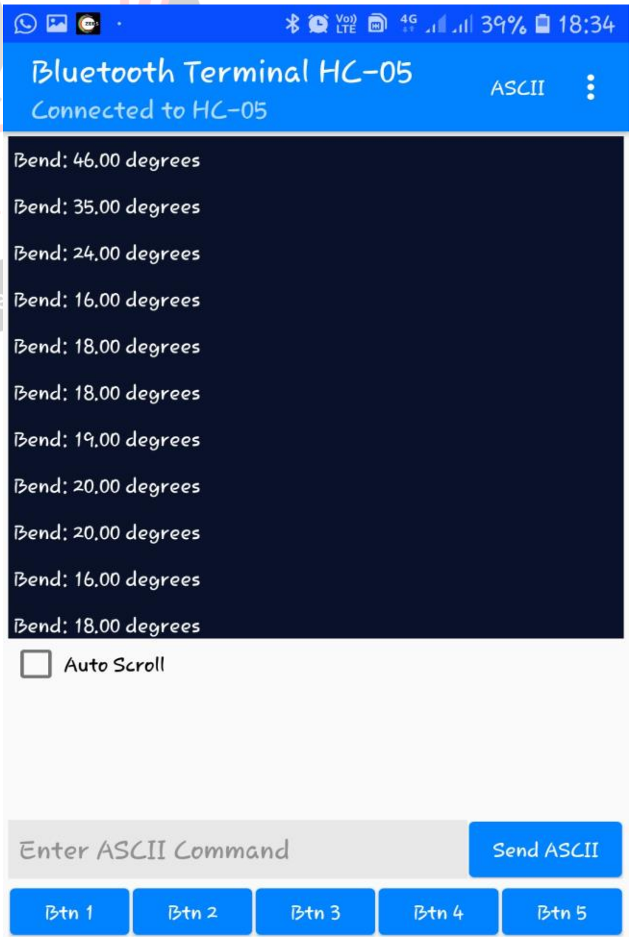

Fig. 7. Knee angle observations in Smartphone display

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One of the enormous advantages of the proposed approach is that it is non-invasive technique for testing human and is immune to the changes in environment. The proposed scheme can aid the clinical professionals in decision making of various medical gait problems. Additionally, simultaneously healthy subjects can also wear to examine their way of walking as regular task to avoid future problems pertaining to their abnormal posture or gait.

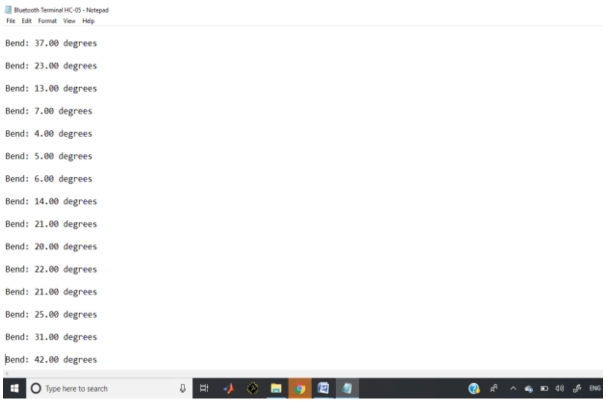

Fig. 8. Log file of Result

V. CONCLUSION

The proposed knee flexion/extension measurement system has good accuracy as a flex sensor used in this scheme has very fine resolution. The Flex sensor used in this project is directly proportional to its flex/bend so that there is no requirement of long algorithm and complex signal process. The characteristics of sensor make the system reliable, accurate, light-weight and less complicated. The accurate positioning of sensor is very important while the measurement system has been using. The measurement system can be very useful for analysis of dynamic posture during clinical investigation of knee biomechanics.

In future, this system still has scope for improvement. An alert system will be integrated with measurement system. Purpose if an alert system will be to make warning while a person wearing knee angle measurement system has encounter abnormality in knee angle during walking.

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