# *Knee Joint Angle Measurement System Using Gyroscope and Flex-Sensors for Rehabilitation*

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***Abstract*— This paper focuses on developing a novel approach for measuring body joint angles, mainly the knee angles, for surface electrical stimulator system. In this work, we only focus on the sensing mechanism for measuring the knee joint angle using wearable sensors. Our system consists of multiple flex-sensors mounted on a supportive cloth and microelectromechanical systems (MEMS) vibratory gyroscope. In Body Sensor Network (BSN) field for medical purpose, body joint angle measurement system is quite important and useful for continuous monitoring in rehabilitation activities especially for Spinal Cord Injury (SCI) patients. Body joint angle measurement system is sensory type systems that provide information about angle movement of body joint. It is usually used at knee and arm joint to monitor the movement while patients do some exercises. This very important and helpful for the therapists and physicians in order to see the effectiveness of rehabilitations training. For knee angle movement evaluation, lower limb joint angles and segment angles were estimated by the Kalman filter from the data measured with wireless MEMS vibratory gyroscope and flex-sensors. Electrical stimulation was applied to the common peroneal nerve or the tibialis anterior muscle by detecting stimulus timing automatically from the data of wireless sensor attached at the back of knee which known as popliteal fossa and shank of the paraplegic side. The developed system performed well in monitoring the effectiveness of rehabilitations training with the knee joint angle measurement average error rate of 6.92°. The comparison between measured data of the gyroscope and flex-sensors for knee joint angle measurement system were also demonstrated.**

***Keywords—Functional electrical stimulation (FES); gyroscope; flex-sensor; knee joint angle***

## I. INTRODUCTION

Continuous monitoring of patients' movements and activities has recently become one of the active research areas in the field of bioengineering and tele-health monitoring. For many medical and rehabilitation applications it is desirable to continuously monitor patients' daily activities at home without visiting hospital. This type of monitoring is beneficial for the therapists and physicians as it does not require patients' physical presence. For example, a wearable body sensor can be designed to measure joints flexion and then transmit the measurements to a hospital via phone line or the Internet. The acquired measurements can then be reviewed by a nurse at the hospital. Patients would be contacted for a hospital visit for a further evaluation upon unsatisfactory results observed in patients' measured data.

One of the approaches for the activity monitoring is to develop wearable sensors and smart cloth and employ them to measure human body movement and joint angles. Traditionally, measuring the range of motion (ROM) has been performed by utilizing standard tools such as goniometer in the hospital. This method needs to be done by a physiotherapist in the hospital and requires great deal of overhead. Thus, a remote sensing technique for monitoring the progress of body joint flexion during regular daily life activities becomes very beneficial [1].

A number of solutions for remotely measuring the body joint angle and movement have been proposed. For example Russell et al. [2] developed an internet-based system to measure the angle of knee joint remotely using a webcam. They evaluated the reliability and validity of assessing knee range of motion via the Internet and provisioned the possible future of Internet-based physiotherapy. A major drawback of this approach is that a patient is restricted to a specified volume/space and also physician should be present and monitor the patients' activities simultaneously. Another example is electronic gloves for measuring the hand posture [3]. The goal of their work was to examine the repeatability performance of the system. Although this approach can measure the hand posture in real time, the system is consisted of 20 Hall Effective sensors. The overall error of this approach for measuring hand posture is about 6.17°[3].

Luinge et al. [4] concentrated on the ambulatory measurement of human body and the orientation of joints. They computed the orientation of upper arm with respect to the forearm by using different sensors like accelerometer and gyroscope. To measure the orientation of inertial measurement unit (IMU), they performed a sensor-to-segment calibration. The authors aimed to improve the possible error of sensor-to-segment calibration by using different calibration movement. Another method which is more similar to our approach is conductive garment (fiber) which is a wearable and comfortable cloth for long term movement monitoring. This method needs one time calibration per patient by a therapist. Although this approach has shown better results compared to the other techniques, the authors mentioned several uncertainties in measuring the resistance across the conductive fiber which resulted in the sensor output not being correct. For instance, joint movement will produce small changes in the fiber tension resulting in a change of fiber resistance which leads to incorrect sensor output.

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Thus, Kalman filtering and its extension to nonlinear systems, are efficient ways to recursively estimate the state of a process using noisy measurements by reducing the mean of the squared error. Kalman filtering has been used in a wide range of applications including aerospace, marine navigation, nuclear power plant instrumentation and demographic modeling, to name a few [5-7]. Another advantage of Kalman filtering is in fusing measurements obtained from multiple sensors. Fusing data measured by multiple sensors can be done using different approaches such as simple averaging, Dempster-Shafer theory [8].

This paper focuses on developing a novel approach for measuring body joint angles, mainly the knee angles, for wireless surface electrical stimulator system. In this work, we only focus on the sensing mechanism for measuring the knee joint angle using wearable sensors. Our system consists of multiple flex-sensors mounted on a supportive cloth worn by the patient under study. When the body joint moves or bends the resistivity of the flex-sensors changes and can be mapped to the angle between the joints by post-processing. In many applications, such as monitoring the progress of body joint after surgery, the precise angle is not as important as consistency of measurement over a period of time [1]. In other words, changes and improvements of the joint flexion are more critical than the accuracy of joint angle measurement. In order to accurately estimate the body joint angle, we model the behavior of joint movement over time and use the model in Kalman filtering to update the measurements obtained by the wearable sensors . In this work we utilize Kalman Filter for accurate estimation of the body joint angle as well as fusing the predicted angle using multiple sensors.

## II. BODY JOINT MEASUREMENT

### A. *Flex-sensor*

In this work we use multiple flex-sensors mounted on a supportive cloth to measure the range of knee motion. The resistivity of the flex-sensor changes when the sensor is flexed. According to the manufacturer's datasheet the range of the sensor resistivity is between 9 kΩ and 22 kΩ [9]. Based on the size of a joint, different number of flex-sensors can be employed.

For example, for the knee joint the flex-sensors can be affixed on top of the knee or can be affixed underneath the knee joint. Whenever the knee bends, the flex-sensors affixed on the supportive cloth worn by a subject, will bend and cause the resistance of flex-sensors to gradually increase. By developing an electronic system, the change in the resistivity of the flex-sensors can be measured.

We utilize a supportive cloth that is made of stretch fabric. Fig.1 illustrates an example of the supportive cloth with attached sensors for studying the knee joint worn by a subject. The supportive cloth has a placement for the knee, which helps in reducing the placement error. Furthermore, lightness of the cloth helps reduce patient's discomfort associated with prolong usage. As the figure shows, two sensors are mounted on the supportive cloth underneath the knee. Due to the space limitation underneath the knee, mounting more than two flex-sensors with the current size (i.e., width is 6.35 mm) side by side of each other is not practical.

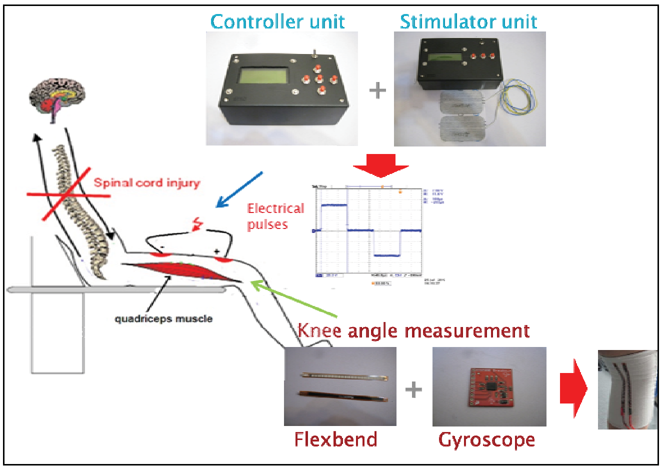

Fig.1: Knee angle measurement system using flex-sensors and gyroscope.

### B. *Gyroscope*

Gyroscope will produce 3 axes which z-axis as a reference axis. At the origin, angle from z-axis to x-axis and y-axis will be at 90˚. While SCI patients move their leg, the angle from reference z-axis to new x-axis with y-axis as a pivot will change. Rotation angle from gyroscope is been calculated based on angular rate that produce by each gyroscope when there is a movement. In this case, idg500 gyroscope with two degree of freedom been used as sensor to measure angle. Idg500 provide angular rate with 2mv/deg/s as its sensitivity to be used to calculate angle from angular rate. Since angular rate is velocity that refers to time in second, angular rate need to be sampled continuously refer to constant time.

### C. *Angle Estimation Using Kalman Filter*

In order to measure the joint angle using multiple flex-sensors and reducing the measurement uncertainty due to sensor noise, we use Kalman filter. This method is easy to use and works well in practical estimation problems. Kalman filter, comprised of two fundamental phases, Predictor and Updater (Corrector), is used to estimate the state of a system with noisy measurements. In the prediction phase, the current state of the system is estimated based on the prior satisfy information (system dynamic model), whereas in the update phase, the predicted state of the system is updated using the measurements obtained by the sensors.

Originally Kalman filtering was developed to track linear systems. It was then extended to track nonlinear systems as well. The nonlinearity can happen either in the dynamic model of a system, or in the measurement part, or in both dynamic and observation parts.

## III. RESULT AND DISCUSSION

In this paper, our prototype of surface electrical stimulator has been used in order to create the knee joint angle movement. As been stated in previous paper [10], a simple low cost current adjustable circuit for electrical stimulator was designed and developed whose output consists of current pulses with a wide range of rectangular waveforms (monophasic/biphasic) ranging from 10-120mA with steps of 2mA and time resolution of

10µs. The circuit also capable of adjusting the current amplitude, frequency and pulse width of the output signals [11]. The main advantages of the device is that the high level of output current amplitude can be controlled by low level of control voltage. The device also has the capability of fine time and amplitude tuning. Moreover, it can produce the vast range of output waveforms and wireless based system using zigbee module. Additionally, the use of low cost electronics components in its structure which makes it economically efficient for being used in various FES research studies as well.

In this paper, we developed a wearable sensor system, comprised of flex-sensors and elastic supportive cloth, to track and measure the knee joint flexion of a subject over time. In our design the two flex-sensors, mounted underneath the cloth, are used to measure the inner angle of the knee joint. In order to measure the flexion of the flex-sensors, we designed and built a microcontroller-based system. For driving the flex-sensors we built a constant current source for each of the sensors using BJTs. Change in the resistivity of the flex-sensors alters the voltage across the collector of the BJTs that collect the constant currents. Thus, change in the joint flexion is converted to change in resistivity of the flex-sensors and then converted to voltage by the constant current source. The collector voltage (0-5V) is then measured by the Analog to Digital Converter (ADC) on the micro-controller board with 10-bit resolution.

Our experiments show that the relation between the voltage (resistivity) and the flexion of the flex-sensors is nonlinear. Fig. 2 and 3 indicate changes of voltage during full range flexion and extension versus time of a subject's knee for two sensors. As the figure shows, the two sensors have different voltage/resistivity responses even though the current sources were kept constant for a wide range of voltage where the current sources operate. In addition, flex-sensors have a nonlinear behavior that varies slightly from one sensor to another sensor.

We designed an experiment to derive the characteristic function of each flex-sensor and its corresponding current source. We used the Kalman filter tracking and fusion system to estimate the knee flexion of a subject wearing the supportive cloth and exercised her knee. During this experiment, the range of motion was decreased and increased to show that the Kalman filter can track the changes in the movement. These results are based on the voltage that we have obtained directly from ADC before sampling it; we can easily convert them to angles. With this result, we assume that the straight leg without any bending is 90°, and angle is decreased by bending the knee.

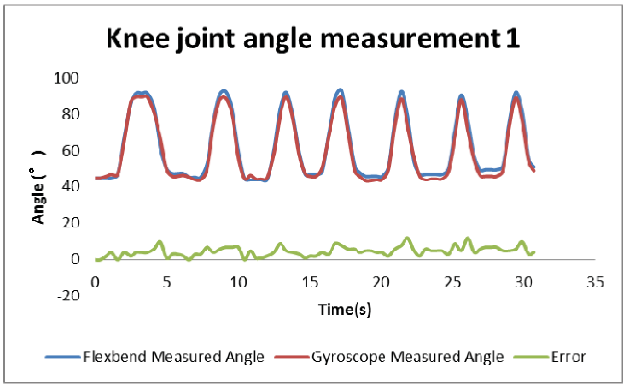

Fig.2: Wireless knee joint angle measurement by flex-sensor1

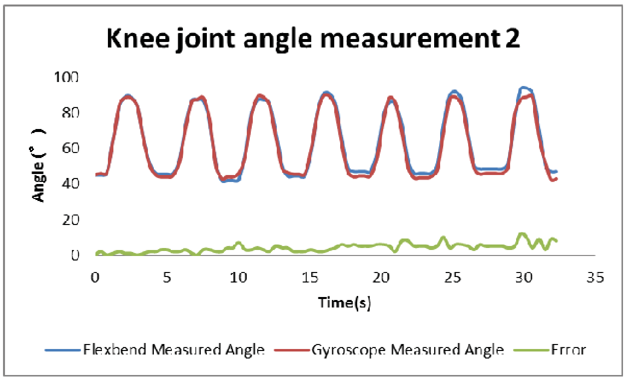

Fig.3: Wireless knee joint angle measurement by flex-sensor2

The measured angles using this approach were compared with the angles simultaneously measured by a gyroscope. These measured values were used as ground truth to evaluate the error rate of our system. Based on our experiments, the average error in measuring the joint angle using flex-sensor1 and flex-sensor2, are 10.99° and 9.36°, respectively. However, when we fuse the two sensors using the kalman filter, the average error rate reduces to 6.92°. As we discussed previously, mounting more than two sensors is not practical and comfortable due to the space limitation underneath the knee. We also studied mounting the flex-sensor on top of the knee, but this limited the knee to be flexed/bent freely and hence it is not practical.

## IV. CONCLUSION AND FUTURE WORK

We developed a wearable sensor system for tracking and measuring body joint flexion. Our system is economical and can be used for different remote health monitoring applications. It is based on multiple flex-sensors which change resistivity upon bending/flexion. We used Kalman filter to predict and fuse joint angles measured by multiple flex-sensors. The main reason that we used multiple sensors is because sensors have errors and the measurements made consist noise. Therefore, by utilizing multiple sensors, the accuracy is increased as the inherent noise is reduced.

Our experiments showed that the developed system can track and estimate the body joint flexion over time. During our experiments we noticed that the flex sensors affixed on the supportive cloth can be damaged if they are not worn properly or gently by the subject. In addition, the lifetime of the sensors are not high since bending may result in fatal breaking. Furthermore, the available flex sensors are wide and affixing more than two sensors on a supportive cloth is not practical. Hence, in the future, we aim to study flex-sensors with better quality, smaller size and utilize them in the design of our system as well as evaluating how further the error in the angle measurement can be improved by fusing more than two sensors. As a real application of this system, we will study the measurement of minimum and maximum angles of the patients' knee joint which are critical results for physicians. This is crucial since the physicians use these results to check the progress of patients' rehabilitation.

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