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Development of Sensory Unit Using Single IMU Sensor for Knee Joint Movement

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***Abstract*— People with paralysis due to neurological disorders such as stroke and SCI require scheduled rehabilitation exercise to regain muscle function and fitness. Most rehabilitation techniques involve some kind of devices or equipment that are dedicated to it. The sensory system is a key component in supporting the function of rehabilitation devices especially when it has elements of monitoring and control. IMU based systems that employ gyroscopes, accelerometer and magnetometer have a growing interest in measuring movement of body part during rehabilitation exercise. Thus, this study proposed the development of a wearable sensory unit using IMU to monitor the knee joint movement during sitting. The system used MPU9250 as a single sensing component to measure angular position and velocity of the knee. Based on the experimental work outcome, the system was proven to be efficient in performing the measurement of angular position and velocity and providing real time data logging for the purpose of data analysis and system control. Enhancement of this single used sensor to achieve the capabilities of two integrated sensors will be the aim for future work.**

Keywords*— *IMU sensor, knee joint, angular position, angular velocity

I. INTRODUCTION

The knee joint supports the body's weight while allowing the lower leg to move relative to the thigh. Many types of movement such as sitting, standing, walking and running involves movements at the knee joint. The knee joint is a hinge synovial joint that allows for flexion and extension. The range of motion in joints that capable to be performed might have an impact on quality of life. The amount of movement at each joint is referred to as range of motion. Extension and flexion are described as normal knee joint movement and was the major movement of the knee.

The human knee is vulnerable to damage due to a variety of mechanisms including hyperextension (including Varus and valgus components), overuse and direct impact[1]. Osteoarthritis due to knee injuries, paralysis due to stroke and SCI also affect knee joint movement. All the stated neurological disorder and injuries can significantly limit daily activities and people with these problems will need rehabilitation treatment to recover. Patients recovering from knee replacement surgery also need rehabilitation to fully recover [2].

The goniometer has been quite popular in measuring knee joint movement such as the method in [3]. However, the goniometer must be carefully aligned with the joint center and it needs to be repositioned every time the targeted joint is changed. Another method, Bennet et al. [4] used digital imaging to measure knee joint movement. However, the main disadvantage of this technique is that it is relatively time consuming. Access to a digital camera, a computer, and the angle measurement software are also potential drawbacks when compared to other techniques.

Somruthai et al. [5] proposed the use of stretch sensors to measure knee range of motion and found that this method can deform without breaking and change shape or size in a consistent manner dependent on the forces applied to them. However, it's necessary to establish the validity and reliability of the methodology under different conditions before it can be considered within a clinical setting. Another method [6] used optical fiber bending sensor to measure knee joint movement. This approach needs to be modified a little more before it can be implemented to monitor knees joint movement. The highest observable angular displacement, based on the predicted output is about 50 degrees which is significantly less than the common rotation range for knee application.

Therefore, it is useful to develop a lightweight wearable rehabilitation system that is free of space constraint for patients[7]. Inertial sensors, also known as inertial measurement units (IMUs), were used to calculate acceleration, angular rate and the magnetic field vector in a three-dimensional local coordinate system[8]. The axes of this local coordinate system represent an orthonormal base that is normally perfectly aligned with the sensor's outside casing with adequate calibration. Nowadays, wearable sensors have been proven to be effective in a variety of health-related applications, including rehabilitation tasks in both kids and adults thanks to their ease of use, robust design, and low cost [9].

Several wearable technologies based on inertial measurement units (IMUs) have been developed and studied to determine the viability of utilizing such systems for knee rehabilitation activities [10]. IMU sensors have been used in a variety of gait analysis techniques, including monitoring postoperative gait abnormalities, detecting falls, determining the type of Parkinson's gait, detecting everyday activities in older persons, and determining the human walking foot trajectory [11]. A system that monitors knee flexion using two wearable IMU sensors proposed in [12] used two IMU sensor that attached to patients' legs to monitor knee flexion at home environment after TKA surgery. Cordillet et al. [8] proposed a method using two IMU sensors to measure knee joint angles during cycling.

A single use of IMU sensor is simpler in setup and suitable for some applications. This work presents the implementation of single IMU sensor in measuring some parameters for knee joint movement. The main components used in this work was an Arduino UNO, an MPU9250 (IMU sensor) and Arduino IDE software. By using serial plotter in Arduino IDE, the angular position and velocity in real-time data logging can be obtained. The rest of this paper is organized as follows. Section II discusses the method used in the design and development. This includes the hardware components and algorithm developed in the program for data acquisition and manipulation. In section III, evaluation of results, and discussions were presented. Lastly, section IV concludes the overall findings.

II. METHODOLOGY

In this section, the system, its components, and the operation of each subsystem will be explained. The design and development of the system also will be explained which includes the hardware and software part.

A. Flow of System Operation

The system operation involves a few steps. The flowchart in Fig. 1 shows the flow of the system operation which involves the process of input data acquisition, calculation of position and velocity, and data plotting.

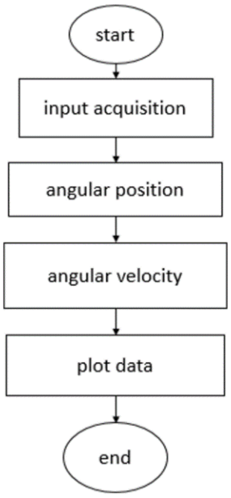

Fig. 1 Flow of System Operation

The system operation started with data acquisition from the input. Since the data representing the variation in knee joint movement parameters, it is highly dependent on the orientation of the IMU sensor itself that acted as the input device. Then, the data is manipulated based on the reference sensor position to obtain the required parameters. In this case, angular position and angular velocity of the knee joint movement are the parameters and targeted final data output.

B. Data Acquisitions

The IMU sensor used in this work is MPU9250. This sensor is a type of high performing device with low power consumption. This sensor is connected to the microcontroller, Arduino UNO where the processing part is performed to gain the data in real time and manipulate using some equations. Through the Integrated Development Environment (IDE), the captured data can be displayed graphically and hence, analysis can be performed to determine the system reliability in providing the accurate final output. Fig. 2 shows the hardware components.

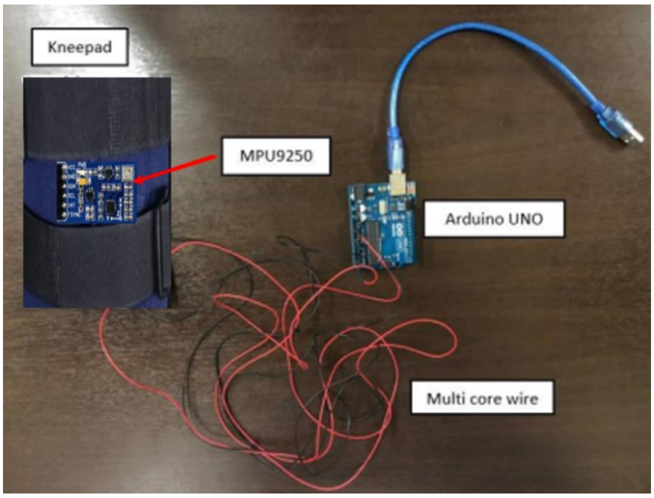

Fig. 2 Hardware Components

To get an appropriate output from the sensor that suits the application to measure the knee joint movement, sensor placement is very important. The sensor must be positioned at the point where it can capture even a small changes of movement. Since the knee joint can be considered to have only one degree of freedom, the point under the kneecap along the shank is suitable to place the sensor. Fig. 3 shows the sensor placement at the subject lower legs. The sensor was aligned to the point to measure the knee swing movement in the sagittal plane.

Fig. 3 Sensor Placement

The knee swing movement was arranged based on the reference angular position of the knee joint. The 0° of the knee joint position was set at full extend, and this value will increase towards 180° when the knee is flexed. Fig. 4 shows the arrangement of knee joint movement.

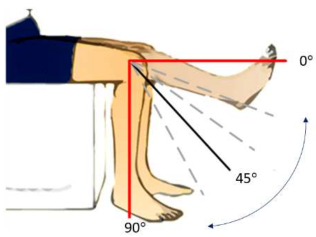

Fig. 4 Arrangements of Knee Joint Movement

C. Angular Position

In order to measure the angular position, the acceleration and magnetometer value from the raw data of IMU sensor must be determined using (1)-(6).

$$accelX = imu.calcAccel(imu.ax) \quad (1)$$

$$accelY = imu.calcAccel(imu.ay) \quad (2)$$

$$accelZ = imu.calcAccel(imu.az) \quad (3)$$

$$magX = imu.calcMag(imu.mx) \quad (4)$$

$$magY = imu.calcMag(imu.my) \quad (5)$$

$$magZ = imu.calcMag(imu.mz) \quad (6)$$

Equation (7) and (8), perform the calculation of pitch and roll angle in radian.

$$pitch = atan2[accelY,(sqrt((accelX.accelX)+(accelZ.accelZ)))] \quad (7)$$

$$roll=atan2[-accelX,(sqrt((accelY.accelY)+(accelZ.accelZ)))] \quad (8)$$

By using (9) - (11), the yaw angle in radian can be determined.

$$Yh=(magY.cos(roll))-(magZ.sin(roll)) \quad (9)$$

$$Xh=(magX.cos(pitch))+(magY.sin(roll).sin(pitch))+ (magZ.cos(roll).sin(pitch)) \quad (10)$$

$$Yaw=atan2(Yh,Xh) \quad (11)$$

Then, by using (12) - (14) the value in degree can be obtained.

$$roll=roll.57.3 \quad (12)$$

$$pitch=pitch.57.3 \quad (13)$$

$$yaw=yaw.57.3 \quad (14)$$

Then, the three readings from roll, pitch and yaw angle were compared and one of it was selected based on the best reading to determine the angular position of the knee joint.

D. Angular Velocity

Angular velocity was determined from the gyroscope value of the sensor given by (15), (16) and (17).

$$gyroX=imu.calcGyro(imu.gx)/57.3 \quad (15)$$

$$gyroY=imu.calcGyro(imu.gy)/57.3 \quad (16)$$

$$gyroZ=imu.calcGyro(imu.gz)/57.3 \quad (17)$$

Then, these gyro x, y and z axis were evaluated, and the gyro z-axis was chosen based on the sensor reference position. The angular velocity was determined by (18) where this equation converted the value in angular position to velocity.

$$Angular\ velocity = d\theta/dt \quad (18)$$

E. Data Plotting

Data that obtained from the IMU sensor were recorded and captured in serial plotter in Arduino IDE software as shown in Fig. 5. Based on the plot, performance of the sensory unit can be evaluated at different movement conditions.

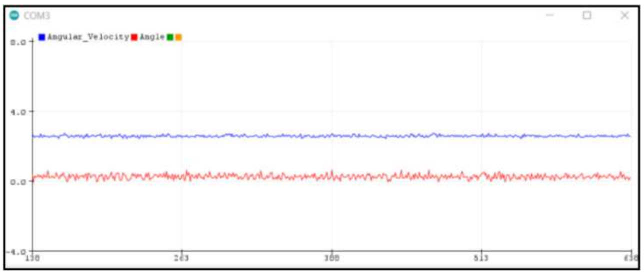

Fig. 5 Plotting in Arduino IDE

III. RESULT AND DISCUSSION

A. Experimental Setup

Performance of the developed sensory system was evaluated on knee swing movement where a subject was set to be in sitting position. The subject's knee joint angle initial position was at 90°. There were two types of movement observed, normal movement and sudden movement, both for full knee and half knee extension.

B. Knee Full Extension Movement

The test subject was sitting at normal position as explained in section *A* and illustrated in Fig. 4. Fig. 6 shows the graph of angular position and velocity recorded.

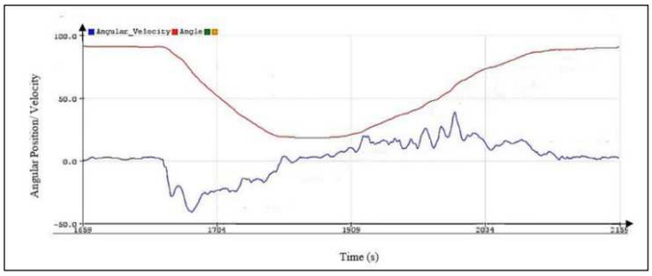

Fig. 6 Plot of Full Knee Extension Movement

The angular position was plotted in red, and the angular velocity was plotted in blue. When the extension occurs, the position of knee joints gradually decreases to 0° indicating the full extend. Next, the test subject holds her leg for a seconds which is shown in the graph as constant value before the flexion occurs and the knee joint angle gradually increases back to 90° indicating it is returned to its initial position.

Referring to the plot of the extension and flexion of the knee, when there are changes in knee joint position, the plot of knee joint velocity also shows changes in the value. Since the movement was not guided by any device that could provide constant velocity, this voluntary knee joint movement seems to always have variation in the velocity. The variation of knee joint velocity was recorded between 0° to 40° per seconds.

C. Sudden Knee Full Extension Movement

The evaluation of the sensory system performance continues with sudden knee extend, hold and sudden return to the initial position. Fig. 7 shows the graph of angular position and velocity captured by the system.

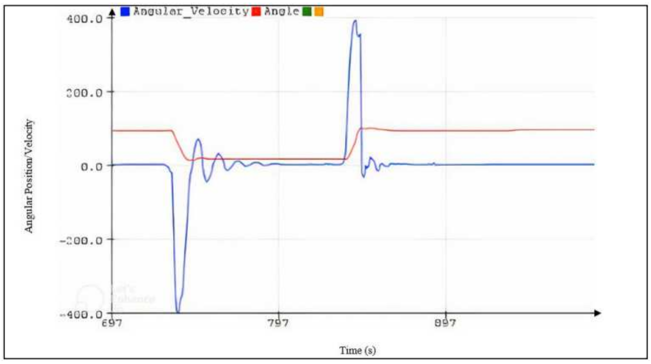

Fig. 7 Plot of Sudden Knee Full Extension Movement

The plot of knee joint position clearly shows the variation in angle when the movement is performed. The two spikes in the plot of velocity clearly shows the movement was done in fast motion. The first spike indicates sudden knee extension, and the second spike indicates knee flexion. The variation of knee joint velocity was recorded between 0° to 400° per seconds.

D. *Knee Half Extension Movement*

In this test, the subject only performs halfway of knee extension to about 45° from the initial position. Fig. 8 shows the plot of angular position and velocity as captured by the system.

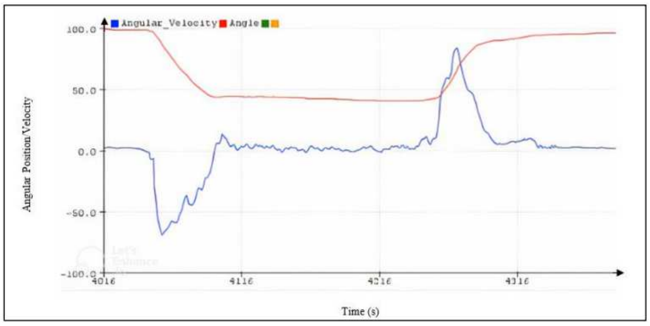

Fig. 8 Plot of Knee Half Extension Movement

In the knee half extension movement, both parameters were properly captured and recorded as shown in the plot. The system was able to capture even small changes in both parameters. The variation of knee joint velocity was recorded between 0° to 60° per seconds.

E. *Sudden Knee Half Extension Movement*

The evaluation also performed on the sudden knee half extension movement and the result is shown in Fig. 9. It seems that the system performed well as what obtained in the previous full extension movement. The variation of knee joint velocity was recorded between 0° to 270° per seconds.

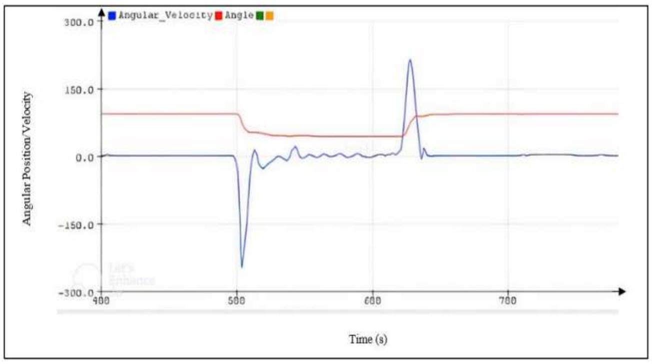

Fig. 9 Plot of Sudden Knee Half Extension Movement

IV. CONCLUSION

This work presents the design and development of a sensory unit using single IMU sensor to measure the parameters of knee joint movement. The knee joint movement can be associated with knee extension and flexion that produce knee swing movement when performed continuously. The developed system successfully captured the two parameters of knee joint position and velocity according to the pre-defined algorithm in the microcontroller program. The captured data shows variations in the two parameters value as the movement was performed in different set up. Factors such as different amount of knee joint torque exerted during the movement also could contribute to the difference in knee joint velocity when the subject tries to achieve the movement target. Further investigation could be performed to observe the sensory unit performance in measuring other types of movement such as sitting to stance and walking, or guided movement using exercise equipment such as cycling and elliptical stepping. Implementation of artificial algorithm is aimed for future work to enhance the single used of IMU sensor in application that usually requires integration of two IMU sensors.

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