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Upper Limbs Extension and Flexion Angles Calculation and Visualization Using Two Wearable Inertial Measurement Units

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***Abstract* - Human motion analysis is widely used in many fields such as physical rehabilitation, athlete training, health status diagnosis and many others. Range of motion (ROM) is an important parameter to evaluate limb's performance during activity of daily. Goniometer is a device often used by physiotherapist to evaluate and analyse the ROM of individual's limb movement. The objective of this works is to develop a system to measure ROM using multiple Inertial Measurement Units (IMU) and transfer data to host computer by using Bluetooth Low Energy (BLE). A software program was develop using Phyton to visualize the motion. In this works, Intel CurieNano board, a six degree of freedom IMU that consist of an accelerometer and a gyroscope was used to calculate the ROM using sensor fusion algorithm. The data from accelerometer and gyroscope were fused using the complementary filter to get the ROM. The motion data was acquired by IMU sensor was sent to a custom program developed in Python through BLE. This custom program displayed the acquired data and visualized the motion in 3D visual model. The IMU sensor was used to measure certain angles at 10°, 30°, 60° and 90° to test its accuracy. The results showed that the angle measurement using IMU sensors has correlation coefficient of 0.9967 where the reference method was goniometer. The wrist flexion and extension angle have maximum error of 7.49° for flexion and minimum error of 1.14° for extension. The ROM measured using IMU sensor has maximum error of 3.57% compared to goniometer. It showed that the IMU's ROM measurement method is as good as goniometer.**

Keywords: Inertial Measurement Unit, Wearable Sensor, Visualization, Upper Limbs, Angle, Complimentary Filter

I. Introduction

Upper Limb's movement is very important to us as we used our hands to conduct daily works such as driving, writing and others at most of the times. There are seven types of upper limb movement such as flexion, extension, pronation, supination, adduction, abduction, and circumduction [1]. Extension and flexion angles can be used to determine the range of motion of the upper limb. Upper limb extension is the movement of forearm more away from upper arm while upper limb flexion is the movement of forearm move toward upper arm. Range of motion is the distance and direction of a joint that can be moved to its maximum capacity. The range of motion for a normal upper limb is 130º where the flexion angle is 130º and extension angle is 0º [2]. Many factors can affect the range of motion of the upper limb such as age, gender, daily activities, and tissue deterioration [3]. Joint angle measurement normally carried out in clinic or

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hospital to measure the range of motion because of tools or instrument such as goniometer that used to measure the joint angle movement required trained personnel such as physiotherapist to operate the instrument [4].

Wearable technology is a technology that can be worn by a person to obtain or record info regarding of the user. Normally, wearable technology has sensors that can be used to track motion, monitor personal health condition, and others. Nowadays, wearable technology is a very popular in medical field especially the application that is related to health monitoring. For example, some devices that include wearable technology such as Mi band, Fitbit can be worn by user to measure heartbeat rate, measure the running speed, monitor sleep quality, step counter and others [5].

Inertial Measurement Unit (IMU) is considered as one of a wearable technology and normally it consists of triaxial accelerometer and triaxial gyroscope [6]. There are many types of IMU in the market such as MPU6050 consists of 6 degree of freedom (DOF) IMU, MPU9150 consists of 9 DOF IMU and others [7]. Accelerometer is a device or sensor that can measure acceleration while gyroscope can measure angular velocity. But there is a limitation for both accelerometer and gyroscope. Accelerometer is very accurate only if the accelerometer stays in stationary while the gyroscope is accurate in short term only [8]. According to Akintade's and Kehinde's works [9], they used two different inertial sensors such as gyroscope and accelerometer to measure the knee joint angle and compare the data of these two different inertial sensors. From their research, they concluded that the accelerometer is good at measuring stationary angle while gyroscope is effective in measuring angle if there is any movement of gyroscope [9].

Nwaizu [6] built a system that can be used to measure the knee joint angle with two accelerometers that placed on shank and thigh. In his research, he introduced three ways to measure knee joint angle. In the first method, two accelerometers were worn around the elbow joint. The formula to calculate the angle is shown in Equation (1).

$$\tan\alpha = \frac{a_{x2}a_{y1} - a_{x1}a_{y2}}{a_{x1}a_{x2} - a_{y1}a_{x1}} \tag{1}$$

where the acceleration in x and y-axis in both accelerometers are represented as (a_{x1}, a_{y1}) and (a_{x2}, a_{y2}). The second method is to find the knee joint angle by subtracting the angle measured on thigh with the angle measured on shank. The last method is to calculate the joint angle between two accelerometers. The formula to calculate the joint angle is shown in Equation (2)

$$\cos\alpha = \frac{a_x b_x + a_y b_y + a_z b_z}{\sqrt{a_x^2 + a_y^2 + a_z^2}\sqrt{b_x^2 + b_y^2 + b_z^2}} \tag{2}$$

where the acceleration in x, y and z axis in both accelerometers are represented as (a_x, a_y, a_z) and (b_x, b_y, b_z). In his study, the angle measured using method two gives a better accuracy as it gives the nearest angle to the angle measured using goniometer [6].

Bennett used Artificial Neural Network (ANN) technique to estimate the knee joint angle using the data obtained from accelerometer and gyroscope from two IMUs where the IMUs are placed on thigh and shank. In his research, data is collected from a person who takes 50 steps in walking with constant speed. Then the data obtained is used to train and test the performance of ANN. In his research, he concluded that ANN can used to estimate the knee joint angle with a 0.97 correlation and a 3.8 degrees root mean square error [10]. Jakob also used accelerometer and gyroscope to measure the flexion and extension of knee joint angle. He placed two IMUs on shank and thigh respectively. He used Extended Kalman Filter to combine the data of gyroscope and accelerometer to overcome the drift problem of gyroscope [11]. However, the problems in using IMU are computational problems for determining the angles also, the effect of offset errors on gyroscope's output as a gyroscope provides rate of rotation and integration of its output is required to determine the amount of rotation [6]. Besides, the Bluetooth updated to Bluetooth Low Energy (BLE) after version 4.0. From research of Siekkinen, He found that the BLE is indeed very energy efficient compared to other technique of wireless communication or it can say as a battery can withstand longer period compared to other technique [12]. The advantages of using BLE are that it can transfer data in two direction and can connect by multiple devices. Therefore, BLE is a suitable technique to use as communication in motion detection.

Multiple IMU sensors can be used classified human activities using deep ConvLSTM network [13-14]. Increasing number of IMU sensors will increase the cost and burden to the individual who want to use it at home. In [13], resampling the dataset and multiclass focal loss technique were used to address the imbalanced dataset and reduced the usage of IMU sensors with comparable results with previous works. Beside IMU sensors, kinematics using video processing methods has been study for home-based stroke rehabilitation program [15]. Several approach to enhance and quantify the rehabilitation process for post-stroke patients have been reported to improve post stroke patient's quality of life [16]. To give an idea for clinician about the force during wrist rehabilitation, a finite element analysis has been carried out. The finite element analysis of wrist showed that stroke model has higher contact pressure compared to healthy model [15].

The aim of this work is to develop a system that can be used to measure upper limb joint angle and rotation angle using wearable sensors and custom built program to receive the data from IMU through Bluetooth and then visualize the movement. The app is built to present the movement with visual 3D model. Besides that, the joint angle is measured using both the system and goniometer. Then compared the data to determine the accuracy of the system.

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II. METHODOLOGY

In this work, two Intel CurieNano, a BLED112 and a computer were used. The software used were Arduino IDE 1.8.5 and Python IDLE2.7.17. The Intel CurieNano is a 6 degree of freedom (DoF) IMU which were placed on the top of the forearm and upper arm to measure the elbow joint angle. BLED112 is an USB dongle that integrated with all the BLE features. Python IDLE2.7.17 is used to build a program to analyze the data from two IMU then result the angle between two IMU and visualize the motion of both IMU.

A. Hardware Aspect

Intel CurieNano is a 6 degree of freedom (DoF) IMU that consists of a triaxial gyroscope and a triaxial accelerometer. The joint angle was calculated based on sensor fusion algorithm using triaxial accelerometer and triaxial gyroscope. Figure 1 shows the Intel CurieNano board.

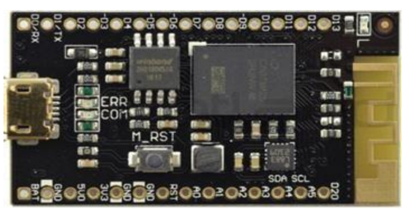

FIGURE 1. Intel CurieNano.

The gyroscope is used to measure the angular velocity while the accelerometer is used to measure the acceleration. The raw data from accelerometer and gyroscope are used to calculate angle between IMU and ground. In this project, the angle between IMU and ground is pitch angle. The formula used to calculate the pitch angle from accelerometer and the formula to calculate the angle from gyroscope are shown in Equation (3) and (4) respectively where a_{ix}, a_{iy}, a_{iz} and w are the raw acceleration in three axis and raw data from gyroscope, respectively.

$$\theta = \frac{a_{iy}}{\sqrt{a_{ix}^2 + a_{iy}^2 + a_{iz}^2}} \qquad (3)$$

$$\emptyset = \int w dt \qquad (4)$$

Since accelerometer can only measure the angle of an object while the object is in static but when the object is moving, the angle will become inaccurate. To solve this problem, the angle of gyroscope and accelerometer are combined using Complementary filter or known as Madgwick filter to obtain the tilted angle. A Complementary filter takes the advantages of the sensors and compensates the disadvantages of the sensors. The formula for the Complementary filter to measure the tilted angle is shown in Equation (5) where n is number of samples.

$$\varphi(n) = 0.9 \times (\varphi(n-1) + \emptyset) + 0.1 \times \theta(n) \qquad (5)$$

Besides the pitch angle, the reading of roll and yaw are required for visualization of the movement. Therefore, reading of roll, pitch and yaw are obtained from the Madgwick filter. Madgwick filter is a new algorithm to calculate roll, pitch and yaw that immune to magnetic distortion. In this project, the roll, pitch and yaw were obtained by using Madgwick filter from Arduino free source library.

The deviation existed in accelerometer and gyrometer when IMU in initial condition. It will make the calculation not accurate. So, a calibration is needed before the reading from both accelerometer and gyrometer used in calculation. When the initial condition, the IMU fixed a position as a reference. Then the offset is calculated, and it will consider in the calculation after that. All the process will automatically run every time IMU activated.

B. Software Development

A program is built in python to display the joint angle and visualization of upper limb motion. The IMU is built in with a Bluetooth module which is Bluetooth 4.0 that can transmit data within a short range. Bluetooth 4.0 is also known as Bluetooth Low Energy (BLE) which consumes a very low power. In this project, topology mesh networking is used to connect the IMUs. The roll, pitch and yaw combined to become a 20-byte message. A data takes up 4 bytes, each data is separated by a 2016 which is “space” in ASCII code so 16 bytes of memory space will be shared in total. The data will store in specific characteristic of GATT profile of BLE. The address of characteristic is set personally. The program will connect with the IMU and send a request to read the data in the characteristic. After the IMU getting the request, the IMU will send the 16-byte data back to the python program.

After the program getting the data, the data will be analyzed and displayed on the display panel. The angle between two IMU is calculated as shown in Equation (6).

$$\theta_{joint} = \theta_{pitch1} - \theta_{pitch2} \qquad (6)$$

The program visualizes the motion based on the roll, pitch and yaw angle from IMU. A 3D visual model is built in python program with using OpenGL. Figure 2 shows the 3D visual model.

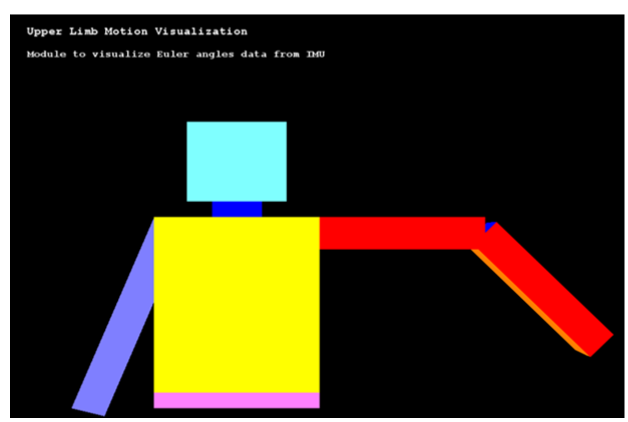

FIGURE. 2. 3D visual model.

The two cuboids of upper limb in the model represented as forearm and upper arm. The two cuboids will move based on the rotation data from 2 IMU that attached on forearm and upper arm. 3 important coding of OpenGL is used in visualization which are glRotatef, glPushMatrix and glPopMatrix. The function of glRotatef is used to rotate all the matrices in screen based on roll, pitch and yaw. This function not only able to rotate an object, but it can also rotate all the object in the screen. So that, glPushMatrix and glPopMatrix were used to avoid other objects involve in rotation. Figure 3 shows the algorithm to visualize upper limb motion.

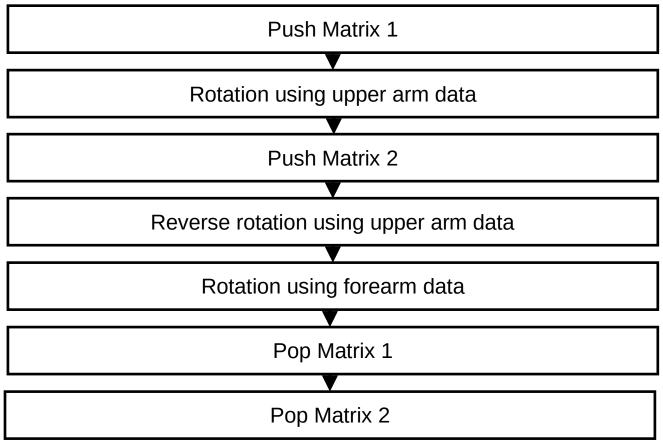

FIGURE 3. Algorithm for upper limb motion visualization.

C. Calibration and preliminary test

The two IMUs sensor is placed on the back of the forearm and upper arm to carry out the joint angle measurement. Before measurement, calibration process needs to be done. The user is required to place his/her hand at a fixed position for a few seconds to carry out calibration. Figure 4 shows the position of hand while calibration process takes place. Make sure the hand is in stationary and stable condition.

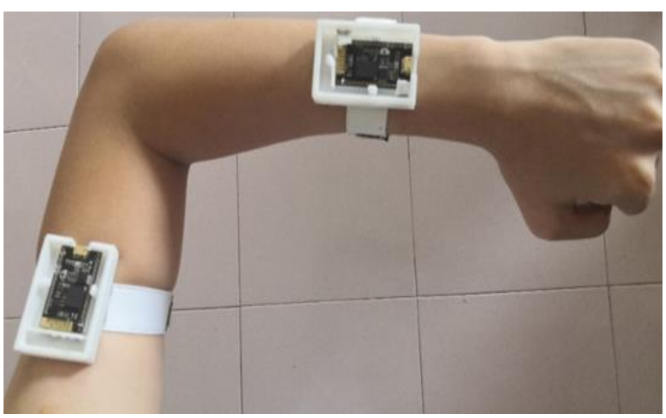

FIGURE 4. Position of the hand while calibration.

The IMU sensors is used to measure some angles such as 10º, 30º, 60º and 90º for over ten trials to determine the accuracy of the IMU sensor. A linear regression relation between the IMU angle and goniometer is plotted to determine the regression relation between IMU angle and protractor angle. The formula to calculate coefficient correlation is shows as Equation (6)

$$R = \frac{n\sum xy - \sum x \sum y}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad (6)$$

For validating of the upper limb joint angle measurement using IMU sensors, a traditional instrument such as goniometer is used to measure the actual angle of the joint. Figure 5 showed the extension angle measurement while Figure 6 showed the flexion angle measurement using IMU and goniometer. Three volunteers were examined to determine the extension and flexion angles using IMU and goniometer over three trials. The joint angles measured using IMU and goniometer were compared.

(a) (b)

FIGURE 5. Extension angle measurement using IMU (a) and goniometer (b).

(a) (b)

FIGURE 6. Flexion angle measurement using IMU (a) and goniometer (b).

III. Results And Discussions

A wearable sensor system was developed that consists of two IMU to measure the upper limb joint angle and python program to display the data and visualize the upper limb motion.

A. Hardware Aspect

An upper limb model was created by using cardboard. This cardboard based rigid model is more stable and will not shake over the time. The shape of model is same as the upper limb. This model consists of two part such as forearm and upper arm. The model can function as human upper limb, it can rotate from 0° to 150°. Figure 7 shows the model of upper limb.

FIGURE 7. **Model of upper limb.**

Intel CurieNano able to collect the raw data from accelerometer and gyroscope and the convert it into roll, pitch, yaw angle. The collected data were joint together to become a 16-byte data with separate by 2016 which is “space” in ASCII. Figure 8 shows the data structure of 16-byte data stored in characteristic BLE.

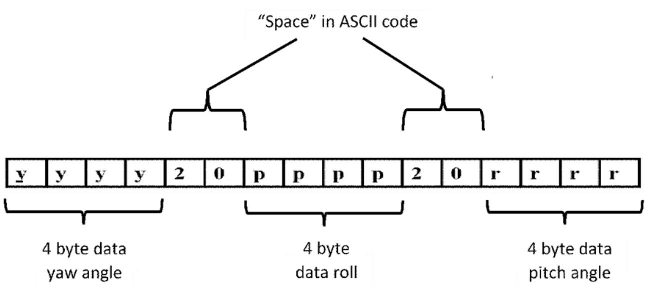

FIGURE 8. **Data structure of 20-byte data stored in characteristic BLE.**

B. Software development

A program was written in Python to display the join angle and visualize upper limb motion is built. Before the program started, the BLED112 must connect to computer. The program starts with scanning the BLE device. The BLE address of both IMU are preset in program so that the program will connect automatically. The characteristic address is also preset before program start. After the IMUs are connected, the data in characters will send to this program. The program will recognize the roll, pitch, yaw and angle IMU from 16-byte data by using “space”. Joint angle between two IMU will be calculated based on Equation (5). The roll, pitch and yaw will display at console python. Figure 9 shows the console of program python.

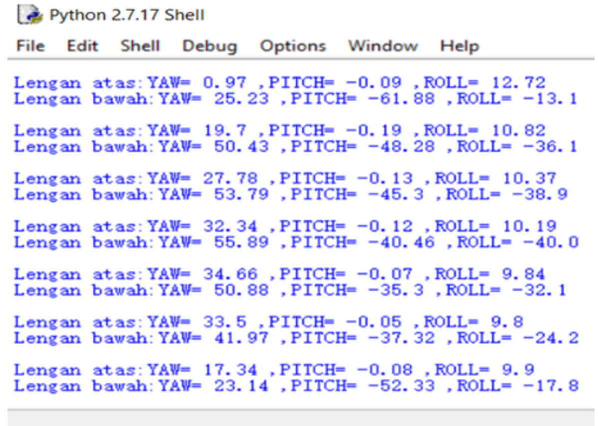

FIGURE 9. **Console of program python.**

Besides, the program visualized the motion of upper limp in real time on a display page by using the data roll, pitch and yaw from both IMUs. There was a visual model with an upper limb built in the page. The upper limb in this model was represented by two cuboids. The all faces of these cuboids were different color to ease for recognition. Besides, this page not only showed the visualization of upper limb but also displayed the joint angle and roll, pitch and yaw from both the IMUs.

By using this program, a few movements were carried out with different angle by using the model upper limb. The movements were capture and compare to the result of visualization. Figure 10 showed the display page of visualization program. Figure 11 shows the result of visualization.

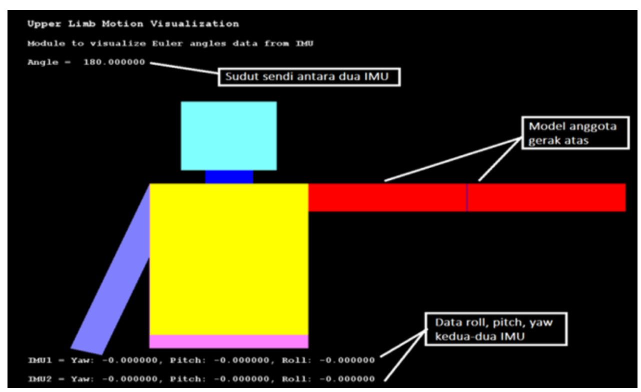

FIGURE 10. **Display page of visualization program.**

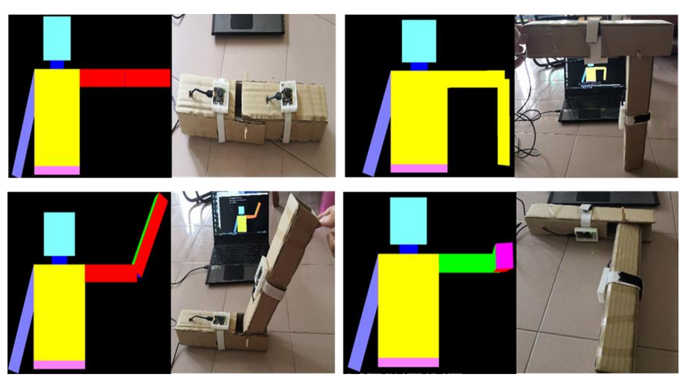

FIGURE 11. **Result of visualization.**

C.Calibration and preliminary test

The IMU system was used to measure some angles such as 10º, 30º, 60º and 90º over ten trials to test the accuracy of the IMU system. Results were shown in Table 1. The effect of drift was eliminated by forcing the output of the gyroscopes to zero. Therefore, the data will not drift when the IMU stays in stationary. The percentage differences of the data obtained were used to determine the precision of the angle. The average percentage difference between IMU angle and goniometer angle was less than 10%. The IMU angle and protractor angle has correlation coefficient of 0.9967. A very high positive correlation coefficient showed a very good positive relation between IMU angle and protractor angle.

TABLE 1. Angle measured using IMU over ten trials.

Trial	10°	30°	60°	90°
1	10.56	31.63	63.54	89.36
2	10.32	31.87	61.78	89.24
3	11.15	32.45	61.25	88.63
4	10.11	31.36	62.63	87.63
5	11.87	30.86	64.11	89.34
6	11.76	30.77	61.32	89.89
7	10.57	31.64	61.68	87.25
8	10.21	31.32	62.98	88.61
9	10.64	32.12	62.74	88.23
10	11.67	31.48	60.56	89.84
Mean	10.886	31.55	62.259	88.802
% of difference	8.86%	5.17%	3.77%	1.33%

Table 2 shows the wrist flexion and extension angle measurement using IMU and goniometer for three volunteers. Both upper limb angles measurement using IMU and goniometer have maximum error of 7.49° for flexion and minimum error of 1.14° for extension.

TABLE 2. Wrist flexion and extension angle measurement using IMU and goniometer of three volunteers.

Volunteers	Movement	Angle (IMU)	Angle (Goniometer)	Error (%)
1	Extension	177.0	175.0	1.14
	Flexion	36.3	38.3	5.31
2	Extension	178.3	175	1.89
	Flexion	24.7	26.7	7.49
3	Extension	176.7	180	1.83
	Flexion	28.7	28.3	1.41

Table 3 shows the range of motion (ROM) of three volunteers measured using IMU and goniometer. The ROM measured using IMU sensor has maximum error of 3.57% compared to goniometer. It showed that the IMU measurement method is as good as goniometer.

TABLE 3. Range of motion for three volunteers.

Volunteers	Upper limb ROM		Error (%)
	IMU	Goniometer	
1	140.7	136.7	2.93
2	153.6	148.3	3.57
3	148.0	151.7	2.44

IV. CONCLUSION

A system used to analyze the upper limb motion was developed. A python program was developed to connect to the IMU sensor using Bluetooth Low Energy. The developed system can be used to measure the upper limb extension and flexion angles. The wrist extension and flexion angles measurement using IMU sensor were sent to the program for display. The motion was visualized on the display panel of the custom Python program using OpenGL. The wrist extension and flexion angles measurement using goniometer and IMU were compared. The IMU sensor was used to measure certain angles at 10º, 30º, 60º and 90º to test its accuracy. The results showed that the angle measurement using IMU sensors has correlation coefficient of 0.9967 where the reference method was goniometer. The wrist flexion and extension angle have maximum error of 7.49° for flexion and minimum error of 1.14° for extension. The ROM measured using IMU sensor has maximum error of 3.57% compared to goniometer. It showed that the IMU's ROM measurement method is as good as goniometer. Future works will focus on the mobile application development and miniaturization of the wearable IMU sensors to achieve low power consumption.

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AUTHOR CONTRIBUTIONS

Chun Ho Chen: Conceptualization, Data Curation, Methodology, Validation, Writing – Original Draft Preparation;

Noor Azah Abd Aziz: Conceptualization, Data Curation, Methodology, Validation, Writing – Original Draft Preparation;

BBB: Project Administration, Writing – Review & Editing;

Kok Beng Gan: Project Administration, Supervision, Writing – Review & Editing.

CONFLICT OF INTERESTS

No conflict of interests were disclosed.

ETHICS STATEMENTS

Our publication ethics follow The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org/

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