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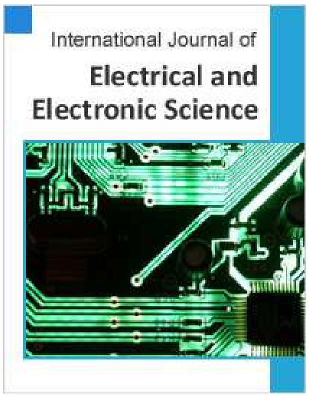

Comparison of Range-of-Motion Measurement Data in Human Knee Joint Using Inertial Sensors

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Abstract
This work uses inertial sensors (accelerometer and gyroscope) to track human knee joint movement and then compares results from these sensors. The MPU-9150 module which combines a tri-axial accelerometer and a tri-axial gyroscope was used as sensors. An mbed NXP LPC1768 was used as microcontroller and ZigBee protocol (XBee Modules) was employed for wireless communication. Both sensors show high repeatability (< 1.0 °), indicating usability. While the gyroscope is good for range of motion measurement, an accelerometer is good for tilt angle measurement. Though data fusion techniques can be used to integrate data from both sensors, it results in an increase in development cost.

1. Introduction

A joint's range of motion can be measured by monitoring the joint's angle. Human joint angle measurement is very important in medical rehabilitation. The knee joint angle data, for example, is essential in quantitative gait analysis for identifying abnormal walking patterns and for characterizing impairments. Traditionally, measuring human joint angle has been performed by utilizing standard tools such as a goniometer [1] which is usually administered by a physiotherapist in the hospital. In addition, the joint angle is most times only measured during standard postures and a continuous measurement of joint angles cannot be captured for advanced assessment. For many medical and rehabilitation applications, however, it is desirable to continuously monitor patients' activities without having to visit the hospital. Thus, an affordable system for monitoring body joint flexion and extension during regular daily life activities is valuable.

Inertial sensors (accelerometers and gyroscopes) are sensors based on inertia (the resistance an object has to a change in its state of motion, and this obeys Newton's first law of motion[1]). An accelerometer is an electromechanical device that measures forces due to acceleration. These forces may be static (for example, force due to gravity) or they could be dynamic- caused by moving or vibrating the accelerometer. A gyroscope on the other hand is an electro-mechanical device that measures angular rate. Measurements with accelerometers and gyroscopes are normally without any external reference.

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1 Newton's first law of motion states that an object either remains at rest or continues to move at a constant velocity unless acted upon by an external force.

This paper describes methods of measuring human knee joint range of motion using two different inertial sensors and then compares data obtained from the sensors. It uses a hybrid (a combination of wireless and wired communications) body sensor network, BSN, with mbed NXP LPC1768 microcontroller and ZigBee protocol for wireless communication Specifically, it uses the MPU-9150 inertial measurement unit (IMU) which combines a tri-axial digital accelerometer and a tri-axial digital gyroscope as sensors [2,3] to track human knee joint angle.

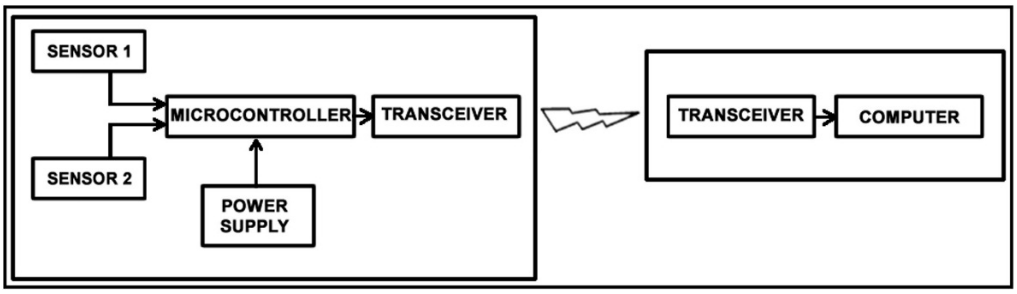

Figure 1. *Block diagram of the hybrid BSN.*

2. Review

A lot of work has been done on using inertial sensors for monitoring position and orientation (especially in navigation). Most of these studies combine accelerometers and gyroscopes in one system while some others use either of the two but none provide a comparison of the inertial sensors. Some of these works are reported below.

Zhou [4] used wearable inertial sensors containing gyroscopes and accelerometers to track human arm movement. The work focused on the motion of the shoulder and elbow joints and integrated data from the inertial sensors for better angle estimates.

Kobashi [5] proposed a way to monitor knee joint angle by integrating MARG sensor (Magnetic, Angular Rate, Gravity) and pressure sensor.

Bakhshi [1] examined various techniques previously used in human body joint tracking before using Inertial Measurement Unit (IMU) to measure and monitor human body joint angles. The work concluded that the accuracy of the IMU measurement system currently outperforms existing wearable systems such as conductive fiber optic sensors and flex-sensors.

Sudin [6] used two gyroscopes to wirelessly track human knee joint angle. In a more recent work, El-Gohary [7] used one IMU on each body segment to design an inertial joint angle tracker. The tracker utilizes the unscented Kalman filter to fuse inertial data from accelerometers and gyroscopes.

The primary goal of this study was to demonstrate the feasibility of using accelerometers and gyroscopes independently for human joint angle monitoring and then comparing the data obtained with the aim of facilitating low cost quantitative assessment of pathological gait (by employing only one of these inertial sensors).

3. Measuring Angle with Inertial Sensors

Figure 1 shows the block diagram of the hybrid body sensor network used in this work. Sensors 1 and 2 are MPU-9150 placed on the thigh and shank respectively. The transceivers are XBee Series 1 modules. This is sufficient for the point to point wireless communication. Sensor 1, Sensor 2 and the XBee are powered via a 3.3 V regulated power supply output pin of the mbed microcontroller.

Data from the MPU-9150 is processed by the mbed microcontroller and wirelessly transmitted to a computer system using wireless ZigBee protocol with the two XBee devices.

3.1. Angle Measurement with Accelerometer

While in proximity of the earth's surface, an accelerometer measures g-force, that is, force due to gravity. Where 1 g is equal to the force of gravity at the earth's surface ($g \approx 9.8\,m/s^2$). So, an accelerometer that sits on the earth's surface will output a g-force of 1 g on the vertical axis.

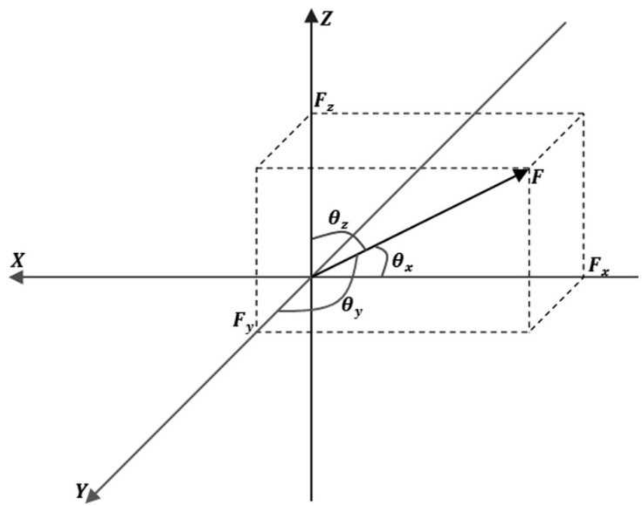

Figure 2. *Tri-axial Accelerometer Representation.*

Figure 2 shows the components of force due to gravity and angles of a tri-axial accelerometer. θ_x is the angle between the x-axis and the accelerometer, θ_y as the angle between the y-axis and the accelerometer, and θ_z as the angle between the

z-axis and the accelerometer. F_x , F_y and F_z are the components of the force due to gravity, F, acting on the accelerometer along the indicated axis. When the accelerometer lies parallel to the earth's surface, it outputs 0 g, 0 g and 1 g on the x-, y- and z-axis, respectively. In this position, the angles calculated on all the three axes should be 0˚.

If A_x, A_y and A_z are the raw accelerometer outputs on the indicated axis and S_{acc} is the sensitivity of the accelerometer, then

$$\left.\begin{aligned} F_x &= \frac{A_x}{S_{acc}} \\ F_z &= \frac{A_z}{S_{acc}} \\ F_y &= \frac{A_y}{S_{acc}} \end{aligned}\right\} \tag{1}$$

The resultant force, F, is given by;

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{2}$$

Therefore, the angles in Figure 2 are

$$\left.\begin{aligned} \theta_x &= \cos^{-1}\left(\frac{F_x}{F}\right) \\ \theta_y &= \cos^{-1}\left(\frac{F_y}{F}\right) \\ \theta_z &= \cos^{-1}\left(\frac{F_z}{F}\right) \end{aligned}\right\} \tag{3}$$

The problem with using an accelerometer to track inclination is that accelerometers are sensitive to both actual (linear) acceleration and the local gravitational field [8]. The accelerometer measures all the forces that are acting on it (and not only the gravitational force). So, when the accelerometer is used to measure tilt, all the forces except gravitational force introduce disturbances (noise) into the measurement as shown in Figure 3. The effect of the noise can be reduced by averaging, using a digital low pass filter of the form,

$$\mathrm{y_i} = \alpha y_{i-1} + (1-\alpha)x_i \tag{4}$$

where y_i is the current angle estimate, y_{i-1} is the previous angle, x_i is the current angle reading from the accelerometer and α is the filter constant with $0 < \alpha < 1$.

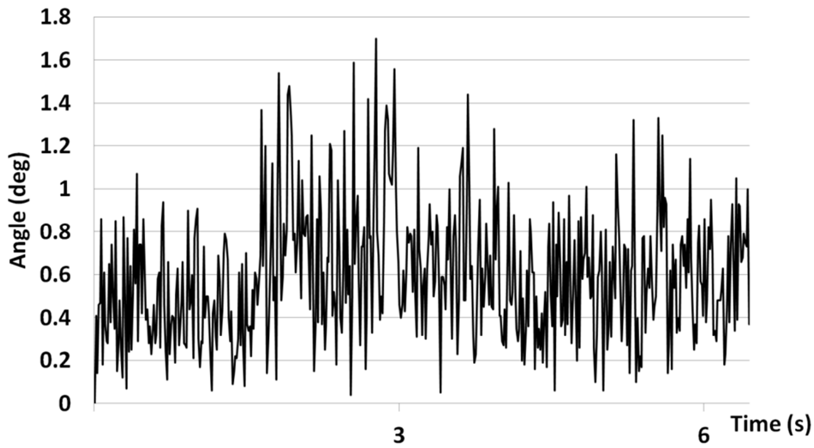

Figure 3. *Accelerometer Angle Data with Noise for a Stationary Platform.*

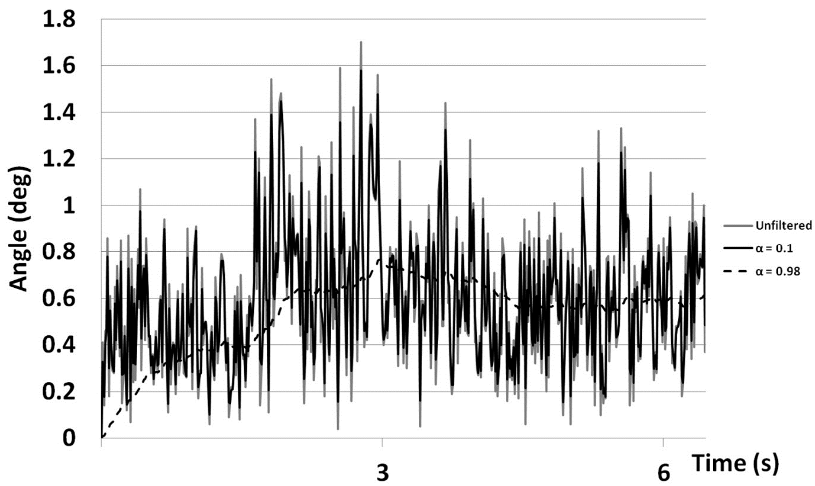

Figure 4. *Filtered and Unfiltered Accelerometer Angle Data for a Stationary Platform.*

The value of α depends on the selected time constant, τ. According to Colton [9], the time constant of a filter is the relative duration of the signal it will act on. For a low-pass filter, signals much longer than the time constant pass through unaltered while signals shorter than the time constant are filtered out. The opposite is true for a high-pass filter. The relationship between α and τ is given by Equation 5. T_s is the sampling time.

$$\alpha = \frac{\tau}{(\tau + T_s)} \tag{5}$$

The graph in Figure 4 shows the effect of various values of α on the accelerometer reading. When α is very high, we have a smooth (almost noiseless) signal but it takes longer time to reach steady state value. With a very low α on the other hand, the signal will reach steady state value quickly but most of the noises are retained. A good choice of α is therefore important.

3.2. Angle Measurement with Gyroscope

The gyroscope is an angular rate sensor, that is, it outputs a signal proportional to the rate of rotation. When the sensor is stationary, the output should be zero.

The output, G, of a gyroscope is given by

$$G(t) = \frac{d\theta(t)}{dt} = \dot{\theta}(t) \tag{6}$$

Therefore,

$$\theta(t) = \int_0^t \dot{\theta}(\tau)\, d\tau \tag{7}$$

For digital systems,

$$\theta(n) \approx \sum_{k=0}^{n} \dot{\theta}(k) T_s \tag{8}$$

So, if G_x, G_y and G_z represent the gyroscope's output on the x-, y- and z-axis, respectively and S_{gyro} is the sensitivity of the gyroscope, then

$$\left.\begin{aligned} \dot{\theta}_x(t) &= \frac{G_x}{S_{gyro}} \\ \dot{\theta}_y(t) &= \frac{G_y}{S_{gyro}} \\ \dot{\theta}_z(t) &= \frac{G_z}{S_{gyro}} \end{aligned}\right\} \tag{9}$$

Therefore, if $\theta_x(t)$, $\theta_y(t)$ and $\theta_z(t)$ represent the angle of rotation of the gyroscope along the indicated axis, then it follows from Equation 8 that

$$\left.\begin{aligned} \theta_x(n) &\approx \sum_{k=0}^{n} \dot{\theta}_x(k) T_s \\ \theta_y(n) &\approx \sum_{k=0}^{n} \dot{\theta}_y(k) T_s \\ \theta_z(n) &\approx \sum_{k=0}^{n} \dot{\theta}_z(k) T_s \end{aligned}\right\} \tag{10}$$

The problem with using a gyroscope for angular measurement becomes obvious from Equation 8. If the gyroscope output, $\dot{\theta}(k)$, is not exactly zero when the gyroscope is not rotating, the measurement will drift. Data obtained from the gyroscope when it is stationary shows that its output is almost never zero. No matter how small $\dot{\theta}(k)$ may be when the platform is not moving, it keeps adding to the angle until the difference between the measured and actual angle becomes significant. The effect of drift is cancelled in this work by using a digital filter (Equation 11) that forces the gyroscope output to zero when the platform is not moving. Figure 5 shows the unfiltered output of a stationary gyroscope (it drifted from 0° to about 1.6° in 6 s) and the filtered angle. The 0.02 threshold in Equation 11 was chosen after experimentation.

$$\begin{aligned} \dot{\theta}(k) &= 0, & for\ \left|\dot{\theta}(k)\right| \le 0.02 \\ &= \dot{\theta}(k), & for\ \left|\dot{\theta}(k)\right| > 0.02 \end{aligned} \tag{11}$$

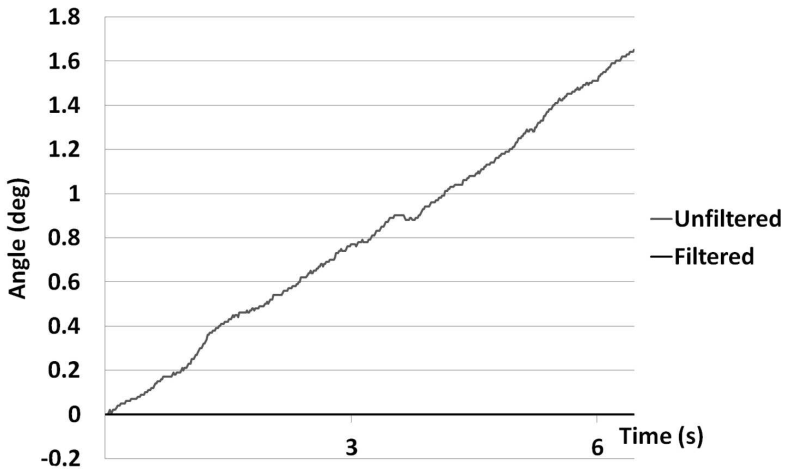

Figure 5. *Gyroscope Angle Data for a Stationary Platform.*

3.3. Repeatability

Repeatability defines the usefulness of a measurement system. Repeatability is measured by calculating standard deviation [10]. The standard deviation measures how concentrated the data are around the mean. The more concentrated, the lower the standard deviation and the higher the reliability. To consider a measurement system's repeatability, it must be tested by the same observer, using the same procedure, at the same location and within a short period of time.

4. Human Knee Joint Angle Measurement

The knee joint angle, θ_{knee}, is measured as the excursion of the knee joint as shown in Figures 6 and 7 (that is, the movement of the shank relative to the thigh).

From Figure 6, the knee joint angle, θ_k, can be calculated as

$$\theta_k = \theta_t + \theta_s \tag{12}$$

where θ_t and θ_s are the thigh and shank angles, respectively and are both obtained from the inertial sensors.

The knee joint angle is taken as the knee joint's excursion starting from an anatomical zero position. The anatomical zero position is the full extension or starting position of the knee joint [11]. One sensor is placed on the thigh to track the thigh movement (θ_t) and another is placed on the shank to track shank movement (θ_s).

Figure 8 shows the flowchart used for obtaining and comparing human knee joint angles obtained from accelerometers and gyroscopes.

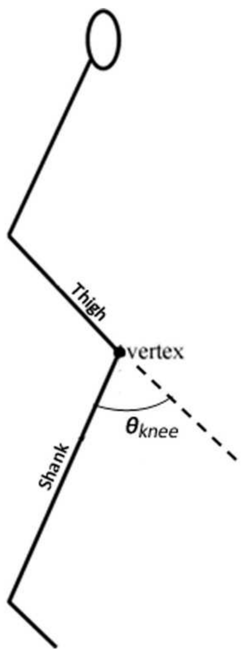

Figure 6. *Segment and Joint Angles.*

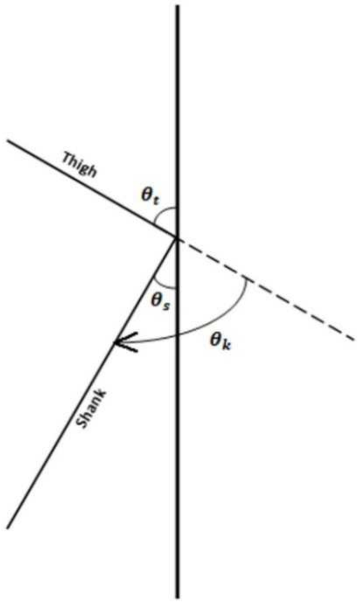

Figure 7. *Knee Joint Angle from the Vertical Reference Position.*

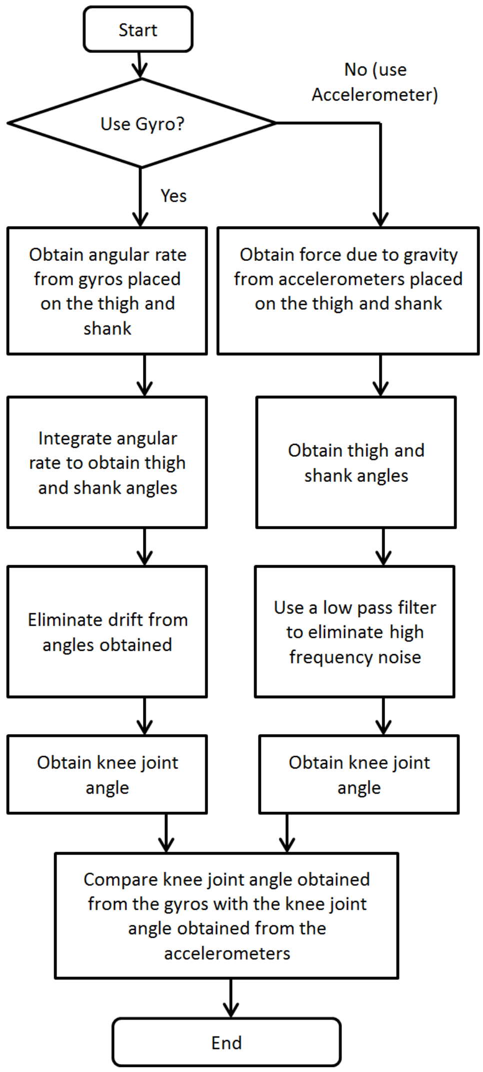

Figure 8. *Flowchart for obtaining human knee joint angle from inertial sensors.*

5. Results

Data obtained from the continuous monitoring of human knee joint angle using accelerometers and gyroscopes during stand-to-squat and walking postures are presented. During the stand-to-squat posture, a subject starts by standing upright, fully extending his knee joint and then squats to full flexion of the knee joint. The subject actually walks during the walking posture.

5.1. Results from Accelerometer

Figures 9 and 10 show graphically the results obtained from the accelerometers during the aforementioned postures. Thigh tilt (θ_t) is obtained from the accelerometer attached to the thigh while that of the shank (θ_s) is obtained from the accelerometer attached to the shank. The knee joint angle (θ_k) is obtained from Equation 12. The digital low pass filter of Equation 4 (with $\alpha = 0.8$) is used on the angle data obtained from the accelerometers.

The angle data obtained from each accelerometer is the present position (or angular tilt) of the accelerometer with respect to the reference position. So, to get the knee joint's excursion from the starting position (the anatomical zero position), angles must be obtained relative to the starting position.

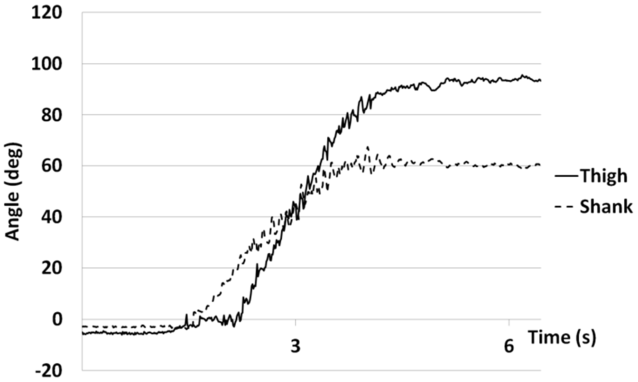

Figure 9a. Accelerometer segments' angle data for stand-to-squat.

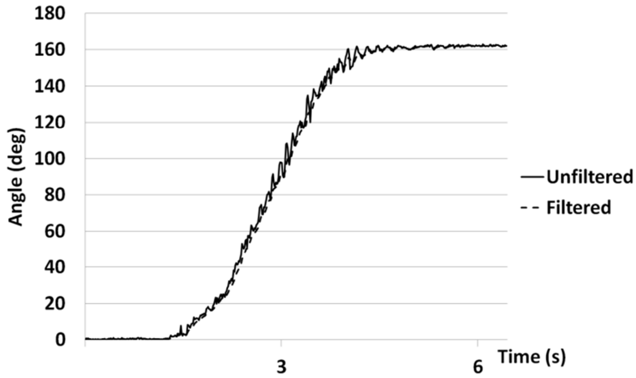

Figure 9b. Accelerometer knee joint angle data for stand-to-squat.

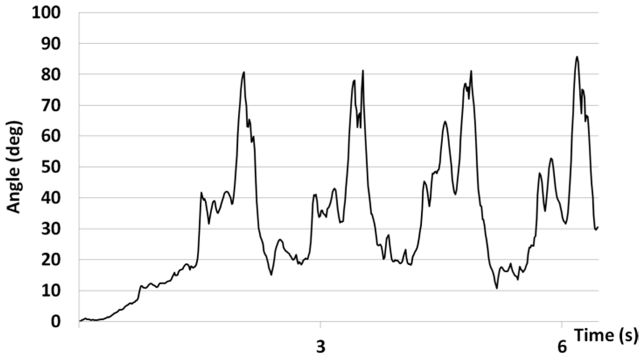

Figure 10. Accelerometer angle data for walking.

For the graphs of Figure 9, the subject stood upright, fully extending the knee joint and then squatted (to full flexion). From Figure 9a, the thigh segment went from $-5.11°$ to $93.25°$ (an excursion of $98.36°$) while the shank segment went from $-2.95°$ to $60.51°$ (an excursion of $63.46°$). The knee joint angle (from Figure 9b), which is the total excursion, is $161.98°$ (after filtering).

In that of Figure 10 the subject walked. This can be used to check for abnormalities in human gait. If both knee joints of a subject are monitored during a movement, there should be symmetry for normal gait.

Table 1. Data obtained over ten trials for stand-to-squat posture using accelerometer.

Trial	1	2	3	4	5	6	7	8	9	10
Angle (°)	150.63	149.45	150.40	148.17	148.44	149.81	150.58	149.22	150.72	149.50

The mean, standard deviation and average deviation are 149.69°, 0.91° and 0.74°, respectively. The low deviations show high repeatability.

Standard and average deviations of knee joint angles obtained over ten trials from the same subject, under the same environmental conditions and the same posture were used for repeatability test. Results are presented in Table 1.

5.2. Results from Gyroscope

Figures 11 and 12 show graphically the results obtained from the gyroscopes. The effect of drift is eliminated by forcing the output of the gyroscopes to zero when the segments' are not moving (rotating). For Figure 11, the subject stood upright, fully extending the knee joint and then squatted (to full flexion). Figure 11a shows that the thigh segment went from $0°$ to $102.9°$ while the shank segment went from $0°$ to $60.76°$. The total knee joint excursion, after filtering, is $163.34°$.

Again, standard deviation and average deviation of the knee joint angles obtained over ten trials (as shown in Table 2) from the same subject, under the same environmental conditions and the same posture were used in the repeatability test. The mean, standard deviation and average deviation are $146.74°$, $0.55°$ and $0.48°$, respectively. These results also show high repeatability. The graph in Figure 12 is that of a walking subject.

Table 2. *Data obtained over ten trials for stand-to-squat posture using gyroscope.*

Trial	1	2	3	4	5	6	7	8	9	10
Angle (°)	147.43	146.59	146.08	146.83	146.89	147.64	146.11	146.68	147.12	146.08

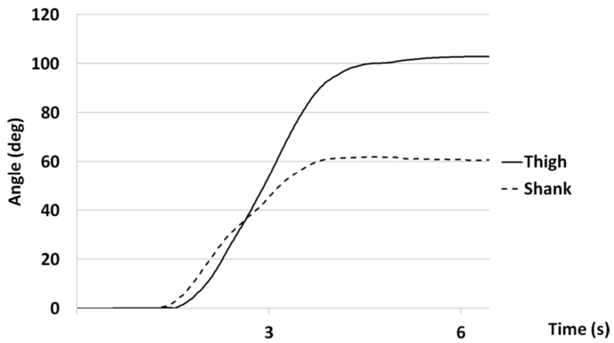

Figure 11a. *Gyroscope segments' angle data for stand-to-squat.*

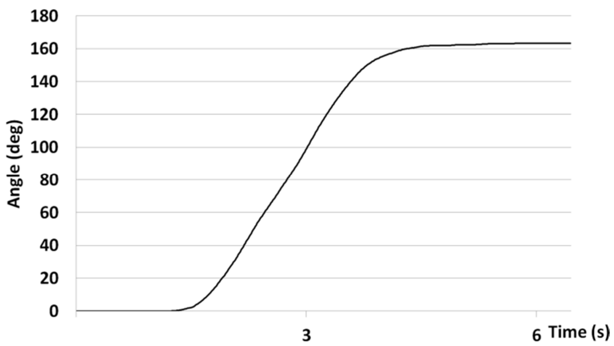

Figure 11b. *Gyroscope knee joint angle data for stand-to-squat.*

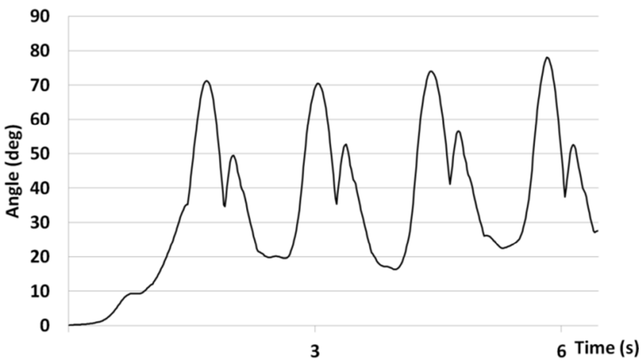

Figure 12. *Gyroscope knee joint angle data for walking.*

5.3. Comparison

From these results, accelerometers are good for tilt (static angle) measurements. The accelerometers (with a digital low pass filter) on the thigh and shank segments will give good segment tilts. However, the knee joint angle is an excursion that starts from an anatomical zero position. This implies that each angle obtained from the accelerometer during an excursion must be subtracted from the starting position (first angle) to obtain the knee joint angle (excursion). This may adversely affect the measurements because the starting angle is an unfiltered noisy measurement.

Also, from the results shown, eliminating drift from the gyroscope makes it good for knee joint excursion measurements as the gyroscope's measurement always start from 0°. So, if the effect of drift is eliminated (as we have already done), the last gyroscope angle is an indication of the knee joint angle. Gyroscopes are however not good for tilt sensing (unlike accelerometers).

Most of the works presented under review (Section 2) integrated both accelerometer and gyroscope data for better angle estimates but the methods presented in this work has shown that any one of the inertial sensors can be used independently to track angles especially in low cost applications. Sudin [6] used only gyroscopes but employed the median filter and the computationally intensive Kalman filter to minimize drift.

6. Conclusion

Each type of inertial sensor has its advantages and disadvantages. While the accelerometer is good for segment's tilt sensing, it has high frequency noise due to the fact that it measures all the forces acting on it and not only the gravitational force. The gyroscope, on the other hand, is good for range of motion (or excursion) measurements, but it drifts.

So, in applications where stationary angles are measured, accelerometer will be the most appropriate because it senses tilt. On the other hand, the output of a gyroscope depends on the rate of change of angle with time and there must be movement for it to be effective. In applications where range of motion (or excursion) is measured, a gyroscope will be the most appropriate.

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