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A Method for Shoulder Range-of-Motion Estimation using a Single Wireless Sensor Node

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Abstract— **This study proposes a method for range-of-motion (ROM) estimation based on the acceleration and geomagnetic data acquired using a single miniaturized wireless sensor node. An experiment on eight shoulder rehabilitation protocols in real human subjects has been conducted, with a sensor placed on user's left and right upper arms and wrists. The experimental results demonstrate the limitations of estimation methods that use sensors placed on skin surface and that, despite being a different body segment, the wrist is a better placement position for sensor-based shoulder joint ROM measurement than the shoulder itself.**

I. Introduction

Range of Motion (ROM) is a widely used clinical parameter for monitoring patient during the rehabilitation process. Normal joint mobility allows many directions of motions. In general, rotational motion can be around an axis perpendicular to one of three body planes, namely, sagittal, coronal and transverse. Motion of body limbs can be classified into two categories namely constrained motion e.g. knee and elbow) and free motion (e.g. shoulder). In the constrained motion, the body limb usually moves in the two-dimensional plane in the 3D space. Hence, only flexion angle is required. For free motion, two angles are usually required namely the deviation from the vertical axis and the angle in the horizontal plane.

Inertial sensors (e.g. accelerometer, gyroscope, and magnetometer) can be attached to body parts to measure on-line range of motion of a patient in the monitoring process. In [1, 2], accelerometers were used to measure and track flexion angles. Accelerometers, however, suffer from a fluctuating offset that can be due to a temperature change or small changes in the structure (mechanical wear) [3]. Lotters et al. [4] proposed an implicit calibration procedure that requires several quasi-static periods of calibration. It was, therefore, impractical to be used in on-line analysis. Luinge [3] adopted the Kalman filter approach to identify and to track the fluctuating offset as well as the gravity vector. The obtained gravity vector was used to determine the inclination of the device, hence the body part. A preliminary study [5] reported how to compute the ROM angle in a three dimensional space based on an accelerometer, along with several constraints and limitations of the technique.

In [6, 7], two accelerometers were attached to two body parts (femur and tibia, upper arm and lower arm, respectively). The range of motion is determined from the difference between the orientations of the two devices. In [8], four body-mounted wearable devices were used to compute the gait kinematics in the sagittal plane. Each wearable device was composed of a uni-axial accelerometer and a gyroscope. The two pieces of information were fused together to obtained a better prediction.

Sensor fusion has indeed been commonly used in range of motion determination. For example, rate gyroscope that allows measuring directly the angular velocity of the limb motion has been integrated into the monitoring system in [9, 10]. Kalman filter framework is generally used as a fusion method since it allows integrating domain knowledge, especially the anatomical constraint, into the estimation procedure [10]. In [11], Peng et al. studied other combination methods derived from rigid-body kinematic theory. The reported results indicated that different methods should be used for near-joint placement and for far-joint placement of the sensor.

A gyroscope can also be used to compute the rotation angle by integrating the gyro signals during the limb motion. This approach is, however, susceptible to an accumulative error. Accelerometers have been used to compensate this error [12, 13], however, more than one accelerometers are required for each body segment. In [14], only one gyroscope and one accelerometer were required per segment. The estimation was based on a pair of virtual sensors that were placed on the center of the rotation by mathematically shifting the location of the physical sensors.

Another way to compensate the accumulative error is to use a magnetometer. The sensor measures the angle deviation from the north magnetic pole, and thus the angle in the horizontal plane. This sensor is generally used when 3D angle measurement is required [9, 15, 16]. The magnetometer, however, is less accurate if it does not lay down flat. Tilt angles computed from an accelerometer are generally used to compensate the geomagnetic signals. As a result, the magnetometer is generally used in conjunction with the accelerometer to measure the limb motion. For example, Héliot et al. [17] used this combination in their study of the knee movement during gait cycle. Zhang et al. [15] used these

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two sensors with anatomical constraints in the 3D ROM angle estimation.

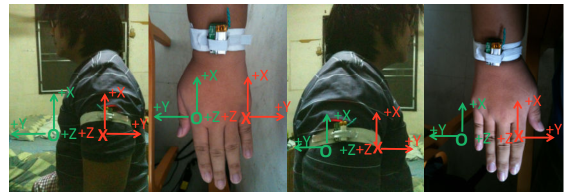
Vision camera is another type of sensors that is often used. In [18], camera information is used in conjunction with inertial sensors. Color tracking using CAMSHIFT algorithm [19] is used to track the wrist of the subject to model arm movement. The fusion between camera and sensor information is done using arm structure relationship. An additional camera is required to solve the occlusion problem. Unfortunately, the preliminary results reported therein only came from an over simplified scenario setting. In [20], particle filter framework was used as fusion method. The experimental setting, however, still seems to be unrealistic. More advanced vision-based system such as the Kinect was considered in [21]. Although Kinect offers a construction of body skeleton which can be used to initialize and to calibrate the inertial sensors, it also suffers from the occlusion problem and the limited field of view constraint. Several studies [22, 23, 24] reported that goniometry gives a more accurate and reliable measurement, compared to visual estimation.

In this study, we propose a ROM estimation method based on tri-axial acceleration and geomagnetic signals acquired from a single sensor node. The method is simple, yet efficient, and thus is suitable for on-node implementation. The effect of sensor placement on the estimation accuracy is studied based on eight shoulder rehabilitation protocols performed by real human subjects.

II. Data Collection

For data collection, the BSN node [25, 26], developed by Imperial College London, is used. The device is equipped with a tri-axial accelerometer (Analog Devices ADXL330 [27]) and a tri-axial magnetometer (Honeywell HMC5843 [28]). Each axis of ADXL330 is sensitive to the acceleration of ±3 g and a resolution of 300 mV/g. HMC5843, on the other hand, measures the geomagnetic field with a minimum full scale range of ±6 Oe (Earth's field is 0.5 Oe). The sensory signals are captured at a sampling rate of 50 Hz and wirelessly transmitted to the PC.

During the experiment, twenty-three subjects, aged between 20 to 55 years, were asked to sit facing the East and perform the eight shoulder rehabilitation routines, namely, 1) flexion, 2) extension, 3) adduction, 4) abduction, 5) horizontal adduction, 6) horizontal abduction, 7) internal rotation, and 8) external rotation. Figure 1 illustrates the different positions (and device coordinates) for sensor placement, i.e., at the left upper arm, left wrist, right upper arm and right wrist. Figure 2 shows the snapshots of some subjects while performing the eight protocols. TABLE I shows the measurement steps of ROM angles in each rehabilitation protocol. In each step, the subjects were asked to hold their arm still for approximately 2 seconds after the specified ROM angle is measured with a goniometer. Figure 3 and Figure 4 show example subplots of acceleration and geomagnetic signals across all the eight shoulder rehabilitation protocols when the BSN node is placed on the right upper arm and right wrist of a specific subject, respectively. A total of 30 datasets were collected: 15 datasets for the upper arm and 15 datasets for the wrist, each of which consists of data acquired from both left and right sides of the body.



(a) (b) (c) (d)

Figure 1. The coordinate systems of the accelerometer (red) and the magnetometer (green) on a) the left upper arm, b) the left wrist, c) the right upper arm, and d) the right wrist.

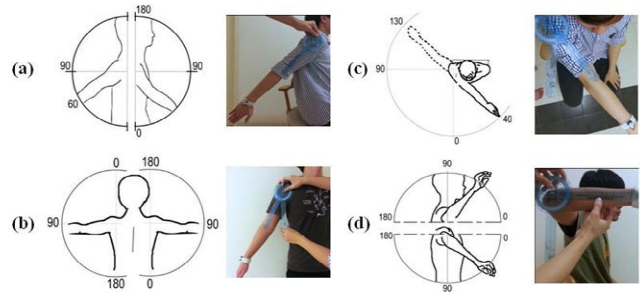


Figure 2. Snapshots of data collection on real human subjects in comparison to the eight rehabilitation protocols: a) flexion/extension, b) adduction/abduction, c) horizontal adduction/abduction, and d) internal/external rotation

TABLE I. Measurement Steps during the Eight Shoulder Rehablitiaion Protocoals.

Rehabilitation Protocol	Measurement Step
Flexion	0°, 30°, 60°, 90° ,120°, 150° and 180°
Extension	0°, 20° and 40°
Adduction	0°, 30°, 60°, 90° ,120°, 150° and 180°
Abduction	0°, 30°, 60°, 90° ,120°, 150° and 180°
Horizontal Adduction	0°, 20° and 40°
Horizontal Abduction	0°, 30°, 60°, 90° and 130°
Internal Rotation	0°, 45° and 90°
External Rotation	0°, 45° and 90°

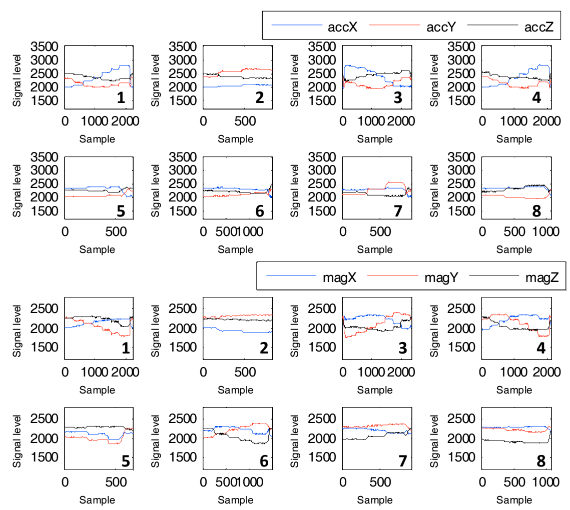


Figure 3.The signal plots of acceleration signals (top) and the signal plots of geomagnetic signals (bottom) across all the eight shoulder rehabilitation protocols when the BSN node is placed on the right upper arm.

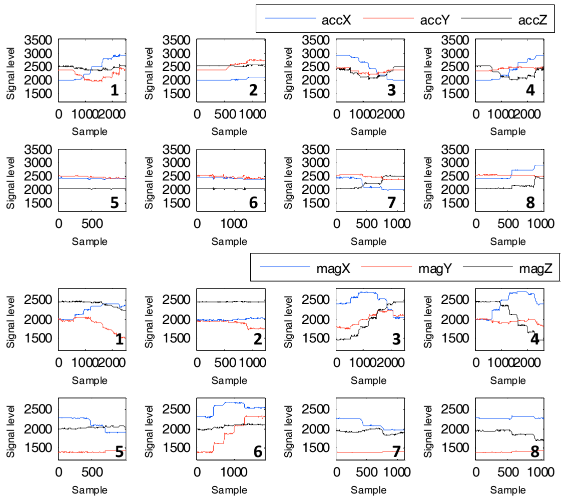


Figure 4. The signal plots of acceleration signals (top) and the signal plots of geomagnetic signals (bottom) across all the eight shoulder rehabilitation protocols when the BSN node is placed on the right wrist.

III. A Combined Use of Accelerometer and Magnetometer for Range of Motion Estimation

From the signal plots, we can observe that ROM estimation based on acceleration signals is suitable for all the protocols, except for protocols 5 and 6, in which the motion is in the horizontal direction. For horizontal motion, ROM estimation based on magnetic field is more appropriate. The placement of sensor on the left and the right parts of the body, along with different starting positions of the eight rehabilitation protocols, incur a change in the device coordinate system. This problem is handled in the existing studies [3, 4] by transforming signals from the local device coordinate into the global coordinate system. However, we have observed that the coordinate transformation is not necessary for the ROM determination

Let $\mathbf{u}$ and $\mathbf{v}$ be the sensor measurement at two distinct positions along the arm rotation. When the accelerometer/ magnetometer is static, only the gravitational force, $\mathbf{g}$, is measured, i.e.

$$\|\mathbf{u}\| = \|\mathbf{v}\| = g \qquad (1)$$

The angle $\theta_{\mathbf{uv}}$ between $\mathbf{u}$ and $\mathbf{v}$ is:

$$\theta_{\mathbf{uv}} = \cos^{-1}\left(\mathbf{u}^T\mathbf{v} / g^2\right) \qquad (2)$$

where $g = \|\mathbf{u}\| = \|\mathbf{v}\|$ is the magnitude of the gravitational force.

Let $\mathbf{R}$ be the rotation matrix that rotates the device coordinate system of the accelerometer into the same reference coordinate system. The rotation does not change the vector magnitude and therefore

$$\|\mathbf{Ru}\| = \|\mathbf{Rv}\| = g \qquad (3)$$

The angle $\theta_{\mathbf{Ru},\mathbf{Rv}}$ between $\mathbf{Ru}$ and $\mathbf{Rv}$ is:

$$\begin{aligned}\theta_{\mathbf{Ru},\mathbf{Rv}} &= \cos^{-1}\left((\mathbf{Ru})^T(\mathbf{Rv}) / g^2\right) \\ &= \cos^{-1}\left(\mathbf{u}^T\mathbf{R}^T\mathbf{Rv} / g^2\right) \qquad (4) \\ &= \cos^{-1}\left(\mathbf{u}^T\mathbf{v} / g^2\right) = \theta_{\mathbf{uv}}\end{aligned}$$

Since $\mathbf{R}^{-1} = \mathbf{R}^T$. Therefore, the ROM angle, θ_t, can be measured from the change in angle from the reference position directly without coordinate system transformation. That is, the angle can be calculated as follows:

$$\theta_t = \cos^{-1}\left(\mathbf{r}_a^T\mathbf{a}_t / \sqrt{\mathbf{r}_a^T\mathbf{r}_a * \mathbf{a}_t^T\mathbf{a}_t}\right) \qquad (5)$$

where $\mathbf{r}_a$ is the reference acceleration vector at the start of the rotation and $\mathbf{a}_t$ is the vector of the normalized acceleration signals at time t, preprocessed by subtracting the DC level from the signals. For protocols 5 and 6, the ROM angle is estimated from the geomagnetic signals instead of the acceleration signals.

IV. Experimental Results

Figure 5 shows the estimated angle errors during the different rehabilitation protocols of the right and left shoulders, respectively. In each subplot, the errors of the angle estimated from the sensor placed on the wrist are compared against that on the upper arm. Based on the results, we can conclude that for shoulder rehabilitation the placement of BSN node on the wrist is generally more suitable than on the upper arm. This is due to the fact the upper arms contain a thick layer of muscles causing the angle between the sensor and the measured body part to change when the muscles are contracted and the upper arm may be naturally twisted along the motion path. Despite the fact that the device is placed on the same body segment as the angle to be measured, at upper arm, high error and error variation are observed in most rehabilitation protocols. In internal rotation and external rotation, the rotation occurs around the upper arm itself. Placing the sensor at the upper arm is, therefore, inappropriate.

When the sensor is placed on the wrist, average RMS errors between 0.86 to 5.05 are obtained for all the protocols apart from right horizontal abduction. In general, the error at 180° for flexion, adduction and abduction is particularly higher than other measurement steps. This is probably because wrist and upper arm are different body segments and when the upper arm is pointing upward at 180°, the wrist tends to move beyond the vertical line.

V. Conclusion

In conclusion, a method for shoulder ROM estimation has been proposed. The algorithm is simple and suitable for on-node implementation. Experimental results show that better accuracy is achieved when the sensor is placed on the wrist. Estimation errors occur due to device rotation caused by muscle contraction. This problem reflects that validation of ROM estimation methods based on placement of sensor or visual tags on skin surface may be less reliable than using traditional goniometer. Although >10° error has been witnessed in certain cases, the estimation results are monotonically increases along with the actual ROM angles and thus can still be used for generating online feedback to motivate the patient during the rehabilitation routine.

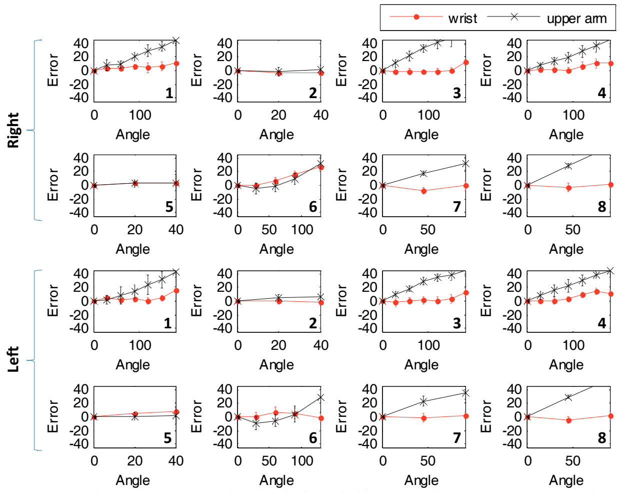


Figure 5. The error bar plots of the difference between estimated and measured ROM angles over eight rehabilitation protocols performed on left and right shoulder. The error values are calculated over fifteen datasets when the sensor is placed on wrists and shoulders, respectively.

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