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Towards the Prevention of Pressure Ulcers with a Wearable Patient Posture Monitor Based on Adaptive Accelerometer Alignment*

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Abstract— **Pressure ulcers are a serious problem affecting over a million patients every year. Despite accepted guidelines for assessing and repositioning high-risk patients, the prevalence of pressure ulcers continues to rise. This paper presents a wearable, wireless vital sign monitor capable of continuously measuring the duration and orientation of a patient's posture throughout the patient's stay in a hospital. Patient posture is determined using a tri-axial accelerometer attached to a patient's torso. A novel set of algorithms are used to process the accelerometer signals to adaptively identify accelerometer alignment on the patient, calculate patient spine angle, and classify patient orientation. A unique pressure ulcer risk index based on these variables is presented to assess a patient's risk for developing pressure ulcers. Experimental results from an 18 subject trial are also presented.**

I. INTRODUCTION

Pressure ulcers are a serious health problem in the United States that affect over 1 million patients each year at an annual cost of over $1.6 billion dollars [1]. Furthermore, between 1993 and 2006 the number of hospital patients diagnosed with a pressure ulcer increased 80% [2]. These alarming statistics indicate an enormous medical need to develop new tools and update clinical practices to prevent pressure ulcer formation in patients who are at risk.

Pressure ulcers develop when soft tissue is compressed between a bony prominence and an external surface for a prolonged period of time, leading to tissue necrosis. Therefore, duration and pressure distribution determined by body position or patient posture are the leading risk factors in the formation of pressure ulcers. Additional risk factors include impaired sensory perception, friction, shear stress, and inactivity [3]. The current recommended healthcare guideline is that patients get assessed for pressure ulcer risk every 24 hours and at-risk patients be repositioned every 1-2 hours [4].

To augment manual healthcare practices non-invasive monitoring solutions have been developed to measure the pressure distribution between a patient's body and the contact surface for bed ridden patients. These monitors utilize a network of pressure sensors embedded in a flexible mat that can provide high resolution maps of a patient's pressure distribution on the contact surface [5][6]. However, these current monitors are capable of providing only a snapshot of the patient's pressure distribution and activity while they are confined to a particular bed and do not provide a continuous representation of posture and activity throughout the patient's time in the hospital. Additionally, installation of expensive pressure sensor beds throughout their facility can be cost prohibitive to many hospitals. A low cost, body worn monitor capable of continuously measuring the duration and orientation of a patient's posture, across the continuum of care in the hospital has the potential to improve the clinical practices designed to prevent pressure ulcers. When this capability is seamlessly integrated into a body worn vital sign monitor, eliminating the need for an additional stand alone device, the acceptance of the pressure ulcer monitor is increased along with its potential to prevent pressure ulcers.

A simple tri-axial accelerometer mounted on a patient's torso provides a low-power, low-cost means of measuring a patient's orientation with respect to gravity. The accelerometer measurements can be processed with a real-time algorithm to estimate the duration and orientation of a patient's posture, score the risk for pressure ulcer development, and wirelessly transmit the information to a central nursing station. One of the biggest challenges in utilizing a body worn accelerometer to measure patient posture is to determine how the accelerometer is aligned on the subject once the clinician has attached the device to the subject's torso. Additional challenges include how to develop an easy to understand user interface to present posture information and a user configurable risk metric or score to alert the hospital care giver of the risk so they can take the appropriate action.

This paper describes a body-worn wireless vital sign monitor with a three-axis accelerometer that is mounted to the patient's torso. The algorithm used to estimate patient posture is described along with the technique used to adaptively determine the alignment of the accelerometer on the patient. The performance of the patient posture measurements calculated with these algorithms are evaluated using human subject data collected with the wireless device.

II. METHODS

A. *The ViSi Mobile Monitor*

All experimental data presented in this paper were collected using the ViSi Mobile Patient Monitoring System. ViSi Mobile is a wireless body-worn vital signs monitor that continuously measures Heart Rate, SpO_2, Respiration Rate, Pulse Rate, and skin temperature. The system is comprised of a wrist module, an upper arm module, and a chest module. Each module contains a three-axis accelerometer to provide information about the patient's orientation and activity. Fig. 1 depicts how the ViSi Mobile attaches to the patient's body.

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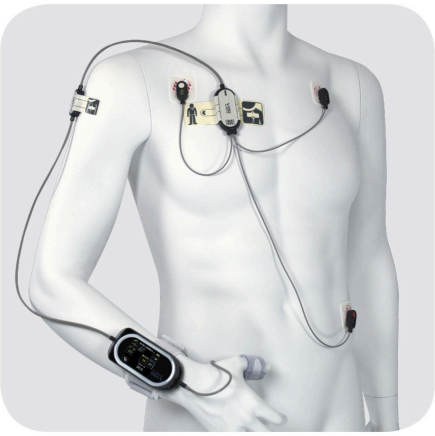

Figure 1. ViSi Mobile Monitor attached to patient.

The wrist module also contains an 802.11 radio used to wirelessly transmit all waveforms to an external computer for observation and data analysis.

B. Posture Measurement

The posture of a patient's torso can be characterized using a set of three angles that are calculated with respect to gravity. At any time the acceleration due to gravity or gravity vector ($\vec{\boldsymbol{G}}$) can be measured in the accelerometer reference frame by a three axis accelerometer when the patient is slightly active or stationary. Three orthogonal basis vectors that define a plane that bisects the midline of a patient's torso are used to calculate the three angles. These three basis vectors whose coordinates are defined in the accelerometer reference frame are the vertical vector ($\vec{\boldsymbol{R}}_{\boldsymbol{v}}$) that is parallel to the superior/inferior axis of the torso plane, the horizontal vector ($\vec{\boldsymbol{R}}_{\boldsymbol{h}}$) which is parallel to the medial/lateral axis of the torso plane, and the normal vector ($\vec{\boldsymbol{R}}_{\boldsymbol{n}}$) that is orthogonal to the torso plane. The torso plane and the torso basis vectors are shown in Fig. 2.

The angle between each basis vector and the gravity vector measured by the accelerometer can be calculated as given in (1). By convention and to provide a more intuitive meaning these posture angles are defined with respect to the ground plane orthogonal to the gravity vector.

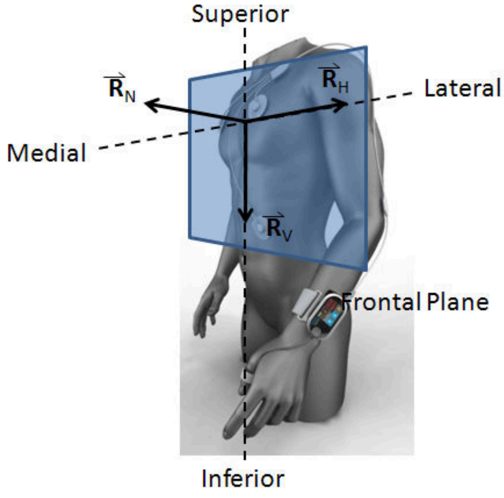

Figure 2. Basis vectors that define a patient's torso plane.

$$\theta_i(t) = \left(\frac{\pi}{2}\right) - acos\left(\frac{\vec{\boldsymbol{R}}_{\boldsymbol{i}}\cdot\vec{\boldsymbol{G}}(t)}{\|\vec{\boldsymbol{R}}_{\boldsymbol{i}}\|\|\vec{\boldsymbol{G}}(t)\|}\right) \tag{1}$$

Therefore, if a patient were standing perfectly erect the torso angles would equal, 0°, 90°, and 0° for the horizontal vector, vertical vector, and normal vector respectively. The three torso angles can be incorporated into a posture classifier to aggregate the angles over specified ranges into discrete posture states.

C. Patient Adaptive Accelerometer Alignment

Posture estimation based on torso angles requires that the three basis vectors be described using coordinates in the accelerometer reference frame. These basis vectors are unique to the individual patient and are dictated by how the accelerometer was attached to the patient's body. Therefore, a technique is required to adaptively identify the coordinates of the three basis vectors following attachment of the accelerometer housing to the patient. This adaptive identification procedure requires several assumptions with regard to patient posture during and immediately following attachment and with regard to where and how the housing is placed on the torso. The assumptions are given below.

1. The positive z-axis of the accelerometer always points towards the patient. (This assumption ensures the ViSi mobile temperature sensor, mounted to the accelerometer housing, is placed against the patient's skin.)
2. The positive x-axis of the accelerometer is angled superior to the medial/lateral axis of the torso plane. (This assumption provides the proper orientation of the ViSi Mobile ECG leads and the connector cable that emanate from the accelerometer housing.)
3. The patient is not lying prone during attachment.
4. The patient in not lying on their side during attachment.
5. The patient is not inverted during attachment.
6. The patient is not lying completely supine during attachment (θ_v > minimum angle).
7. The spine is aligned during attachment; the patient is not leaning to their right side or left side.
8. The accelerometer is attached to the upper torso of the patient below the clavicle and the angle of a patient's upper torso with respect to the torso plane ($\emptyset$), can be approximated as a constant for the patient population.

The first step in the procedure is to identify the three coordinates of the normal vector as given in (2) using three equations to solve for the three unknowns.

$$\vec{R}_n = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \tag{2}$$

The normal vector is constrained to have a unit length as given in (3).

$${n_x}^2 + {n_y}^2 + {n_z}^2 = 1 \tag{3}$$

Based on assumptions 1 and 8, the x and y coordinates on the normal vector are constrained to a circle defined by the torso angle as given in (4).

$$n_x{}^2 + n_y{}^2 = \sin(\emptyset) \tag{4}$$

The third constraint equation is based on assumptions 3-7, which is to minimize the distance between the normal vector and the gravity vector measured at the time of alignment as given in (5).

$$min\left\{(g_x - n_x)^2 + \left(g_y - n_y\right)^2 + (g_z - n_z)^2\right\} \tag{5}$$

This system of equations can be solved using a constrained optimization technique such as the Method of Lagrange Multipliers.

The second step in the procedure is to identify the three horizontal vector coordinates as given in (6).

$$\vec{R}_h = \begin{bmatrix} h_x \\ h_y \\ h_z \end{bmatrix} \tag{6}$$

The horizontal vector is constrained to have a unit length as given in (7).

$$h_x{}^2 + h_y{}^2 + h_z{}^2 = 1 \tag{7}$$

A second constraint is based on assumptions 3-7, the gravity vector is orthogonal to the horizontal vector as given in (8).

$$\vec{R}_h \cdot \vec{G}(t) = 0 \tag{8}$$

The third constraint is derived from the fact that the horizontal vector is orthogonal to the normal vector identified in the previous step as given in (9).

$$\vec{R}_h \cdot \vec{R}_n = 0 \tag{9}$$

A closed form solution for the coordinates of the horizontal vector can be determined using these three equations.

Finally, the coordinates of the vertical vector can be determined as the vector cross product of the other two basis vectors as given in (10).

$$\vec{R}_v = \vec{R}_h \times \vec{R}_n \tag{10}$$

Assumption 2 is used to ensure that the horizontal vector identified in this procedure points toward the patient's left side. If the x-axis coordinate is less than zero the direction of the horizontal vector must be inverted and a new vertical vector identified using the updated horizontal vector in (10).

The adaptive identification procedure described in this section relies on several assumptions, in cases when the device is attached to the subject under conditions that violate these assumptions the algorithm must identify these violations and rely on a predetermined set of default basis vectors which could limit the accuracy of the posture measurement.

III. RESULTS

A set of experiments were carried out to evaluate the performance of the accelerometer alignment and posture measurement algorithms. Posture data were collected from eighteen subjects under an Institutional Review Board approved protocol.

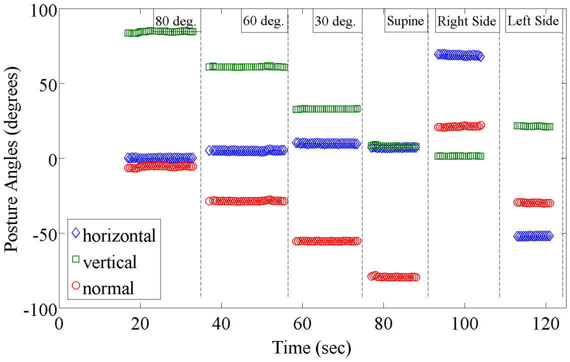

Figure 3. A sample time series of the three estimated posture angles

The experiments included both male and female subjects whose BMI's spanned a wide range from normal to obese (21-32). All accelerometer data was collected using the ViSi Mobile monitor. Data from the monitor was transmitted via an 802.11 radio to a wireless access point connected to a laptop computer. Prior to the experiment the test subject was asked to attach the accelerometer housing to their body using an adhesive patch and not to violate assumptions 1 and 2 described in the previous section. The attachment of the accelerometer housing was concealed by the subject's clothing and blinded to the investigators.

Accelerometer data was collected with the test subjects seated or lying on a Stryker™ transport stretcher. The posture of the test subject was periodically altered by adjusting the angle of the back rest among four positions. The approximate angles of the four positions were 80°, 60°, 30°, and 0°. The test subject posture was maintained at each position for approximately 30 seconds. Additionally, subjects were asked to lie on their left and right side for approximately 30 seconds in each position. The alignment and posture algorithm were implemented in Java and offline processing was performed in MATLAB. The three accelerometer signals were sampled at 50 Hz and posture angles were updated every half second. A time series of the three posture angles calculated from the accelerometer data recorded during one of the tests are shown in Fig. 3.

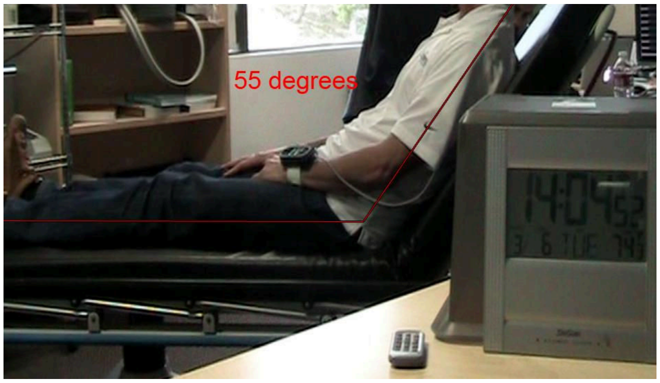

Figure 4. A sample image depicting the reference spine angle

A video camera was employed to record the posture of the patient throughout the experiment. Later this video was used to determine a reference spine angle for each patient's torso. A sample video image from one of the tests along with the reference angle is shown in Fig. 4.

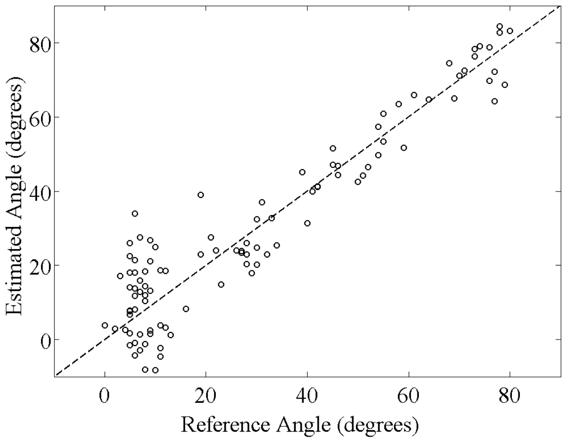

Figure 5. Reference spine angle vs. estimated spine angle

There are three primary posture metrics that will be used by the ViSi Mobile Monitor to evaluate a patient's potential risk for developing pressure ulcers, they include posture duration (t_p), spine angle (θ_v), and orientation with respect to the bed surface (front-side, back-side, right-side, left-side). A total of 102 different postures and spine angles were recorded during the course of the experiment for the eighteen test subjects. A plot that compares the reference spine angle to the spine angle estimated using the accelerometer algorithm presented in this paper is shown in Fig. 5.

A decision tree classifier, based on the estimated torso angles, was implemented to determine the orientation state of the test subjects (front-side, back-side, right-side, and left-side) as they were moved to the different postures. Table I summarizes the performance of the classifier and the spine angle estimation.

TABLE I. POSTURE EXPERIMENT SUMMARY

Spine Angle Error Bias	Spine Angle Error Std. Dev.	Correct State Classification	Total States
0.4°	9.4°	99	102

IV. DISCUSSION

The results presented in this paper demonstrate that spine angle and body orientation can be measured with a relatively high degree of accuracy and precision using an adaptively aligned accelerometer. The adaptive alignment algorithm presented in this paper requires few assumptions such that attachment of the accelerometer by a healthcare worker can be performed expediently and with little training.

Established pressure ulcer risk assessment scales, such as the Braden Scale, cite pressure duration and intensity as major contributing factors to pressure ulcer development [7,8]. Furthermore, deep tissue pressure distribution in patients is strongly dependent on body posture [9, 10]. We propose a real-time metric to characterize a patient's pressure ulcer risk. The **P**ositional **P**ressure Ulcer **R**isk **I**ndex (PPRI) is a function of spine angle (θ_v), orientation, and posture duration (t_p), as measured by the wireless, body worn vital sign monitor described in this paper.

The proposed PPRI is a value between 0 and 1 that is generated using a logistic regression model as given in (11).

$$PPRI(t) = \frac{1}{1 - exp(-z_i)} \qquad (11)$$

A unique logit variable (z_i) and set of regression coefficients (a_i, b_i, and c_i) are used to adapt spine angle and posture duration for each of the four orientations as given in (12).

$$z_i = a_i\theta_v + b_i t_p + c_i \qquad i = 1,2,3,4 \qquad (12)$$

In future work the regression coefficients and the PPRI value used to classify pressure ulcer risk will be determined empirically from data collected on hospitalized patients.

V. CONCLUSION

A low cost, wireless, body worn monitor capable of continuously measuring the duration and orientation of a patient's posture across the continuum of their care in the hospital has the potential to improve the clinical practices used to prevent pressure ulcers. The wearable vital sign monitor presented in this paper that includes an embedded torso accelerometer and adaptive posture algorithms demonstrated a capability to accurately measure spine angle as well as classify the patient's orientation. A risk index was proposed to fuse the calculated posture variables into a **P**ositional **P**ressure Ulcer **R**isk **I**ndex (PPRI) to provide real-time feedback to healthcare workers. Future work based on clinical data collected from hospitalized patients will be required to tune the model and assess the efficacy of the index to guide care and reduce the incidence of pressure ulcers.

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