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Novel approach to ambulatory assessment of human segmental orientation on a wearable sensor system

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ABSTRACT

A new method using a double-sensor difference based algorithm for analyzing human segment rotational angles in two directions for segmental orientation analysis in the three-dimensional (3D) space was presented. A wearable sensor system based only on triaxial accelerometers was developed to obtain the pitch and yaw angles of thigh segment with an accelerometer approximating translational acceleration of the hip joint and two accelerometers measuring the actual accelerations on the thigh. To evaluate the method, the system was first tested on a 2° of freedom mechanical arm assembled out of rigid segments and encoders. Then, to estimate the human segmental orientation, the wearable sensor system was tested on the thighs of eight volunteer subjects, who walked in a straight forward line in the work space of an optical motion analysis system at three self-selected speeds: slow, normal and fast. In the experiment, the subject was assumed to walk in a straight forward way with very little trunk sway, skin artifacts and no significant internal/external rotation of the leg. The root mean square (RMS) errors of the thigh segment orientation measurement were between 2.4° and 4.9° during normal gait that had a 45° flexion/extension range of motion. Measurement error was observed to increase with increasing walking speed probably because of the result of increased trunk sway, axial rotation and skin artifacts. The results show that, without integration and switching between different sensors, using only one kind of sensor, the wearable sensor system is suitable for ambulatory analysis of normal gait orientation of thigh and shank in two directions of the segment-fixed local coordinate system in 3D space. It can then be applied to assess spatio-temporal gait parameters and monitoring the gait function of patients in clinical settings.

1. Introduction

In the medical field, parameters of human motion, especially the orientations of lower limb segments, are very important for clinicians to determine suitable treatments for patients (Findlow et al., 2008; Favre et al., 2008). Gait analysis has become an effective tool for quantifying surgical intervention effects and evaluating patients' conditions (Aminian et al., 2004). Therefore, it is essential to detect the orientations of lower limb segments in biomechanical applications. And various kinematic sensor techniques and sensor-based wearable systems have been developed for gait analysis (Mayagoitiaa et al., 2002; Turcot et al., 2008; Kavanagh and Menz, 2008; Nyan et al., 2006; Liu et al., 2008; Williamson and Andrews, 2001).

As far as the measurement of certain lower limb segment orientation is concerned, joint angle has been estimated using accelerometers and/or gyroscopes (Engin et al., 2005; Roetenberg et al., 2007). However, when accelerometers were used to measure the accelerations of human lower limb segments, the measured signal along each sensitive axis was a resultant acceleration composed of gravitational, translational and rotational accelerations and noise, which cannot be separated (Kavanagh et al., 2006). Hence, the actual resultant acceleration could not be simply integrated as angular acceleration alone to predict the rotational angular velocity and displacement for segmental orientation, since it was composed of translational and gravitational acceleration components and noise at any time when the subject moved at any speed, which would lead in integral errors (Zijlstra et al., 2008). If the angular displacement of the rotational segment is calculated using the equation $\theta=(180/\pi \arcsin(a_z/g))$, where a_z is the measured vertical acceleration, the measured subject must remain still, or the linear acceleration component must be neglected. Dejnabadi et al. (2006) obtained the angular displacement of the rotational segment by numerically integrating the angular velocity captured by a gyroscope, but the integrated result was distorted by offsets and drifts. Luinge and Veltink (2005) presented another method, but the gyroscope offset had to be continuously recalibrated and

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the orientation had to be continuously corrected. Dejnabadi et al. (2005) presented a method to solve the contradiction, obtaining the angular displacement with both accelerometer and gyroscope, and switching between the two sensors according to the wave frequency of the body segment. However, it proved difficult to achieve an accurate switching frequency. Karol et al. (O'Donovan et al., 2007) presented a methodology for joint angle measurement, but it combined three kinds of sensors (gyroscope, accelerometer and magnetometer) and the study was limited to a static system (no global rotational or linear acceleration existed). Bogert van den et al. (1996) presented a method for inverse dynamic analysis in three dimensions using only accelerometers mounted on the upper body. He just presented the equations for calculating the total resultant force and moment on a body segment but not solve the equation for segmental orientation.

This paper therefore presents a simple algorithm that uses only data from accelerometers attached to the subject in order to measure lower limb orientation and other gait parameters. The proposed double-sensor deference algorithm is capable of measuring the rotation of a body segment about two local axes. It is proposed the algorithm should be capable of calculating thigh body segment flexion/extension and abduction/adduction angles during gait in 3D space and because it does not use gyroscope data, it should not contain the gyroscope integration errors reported by others.

Actually, the gravitational acceleration and inertial acceleration due to translation and rotation and noise cannot be separated out of the measured signal (Hagemeister et al., 2005). When a triaxial accelerometer is attached to a rigid body segment at a known position $\mathbf{r}$ in a segment-fixed coordinate system, the measured acceleration $\mathbf{a}$ is shown as follows:

$$\mathbf{a} = \mathbf{R}(\mathbf{g}+\mathbf{a_o})+\dot{\boldsymbol{\omega}}\times\mathbf{r}+\boldsymbol{\omega}\times(\boldsymbol{\omega}\times\mathbf{r}) \tag{1}$$

where $\mathbf{R}$ is the attitude matrix of the body segment with respect to the ground, $\mathbf{a}_o$ is the acceleration of the origin of the segment coordinate system with respect to ground, $\mathbf{g}=(0,\ 0,-g)^T$ is the gravitational field, and $\boldsymbol{\omega}$ is the angular velocity of the rigid body, expressed in the body-fixed coordinate system. Additionally, when the sensors are attached to the lower limb, the skin motion artifact due to impact loading and muscle activation can readily contaminate signals. The measurement of body segment orientation from only accelerometer data therefore requires the assumptions explained below and the equations developed in the following section.

It was amused that the lower limb segments were rigid segments and the subjects walked in a straight forward way with very little trunk sway, skin artifacts and no significant internal/external rotation of the leg. When two accelerometers are attached at two different positions with each corresponding axis in the same directions, the gravitational acceleration, translational acceleration, skin motion artifact and other noise acting on the two sensors should be the same except the rotational acceleration. To exploit the difference between the rotational accelerations, a new and simple method based on a double-sensor difference based algorithm was expatiated to estimate the rotational angles of lower limb segment in two directions for the segmental orientation in 3D space. To validate the method, a wearable sensor system based only on triaxial accelerometers was developed and tested on a mechanical arm and human segments.

2. Methods and materials

2.1. Double-sensor difference based algorithm for analyzing the orientation of a rotational rigid body in the 2D frame

First, to analyze the rotation of a rigid segment in 2D coordinate frame, three reference coordinate systems are introduced: one global reference frame *XOZ* is defined at the pivot point of the segment, another two sensor-fixed coordinate frames $x_Ao_Az_A$ and $x_Bo_Bz_B$ are defined at the positions A and B on the segment with the z_A and z_B axes along the rigid segment, as Fig. 1 shows. When the pivot point is fixed in the global frame, the relationship between accelerations and angular displacements at positions A and B are given by the following expression:

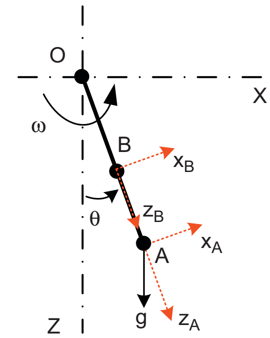

Fig. 1. Motion of a rigid body in 2D coordinate frame.

$$a_{Ax} = \ddot{x}_A + g\sin\theta = r_A\ddot{\theta} - g\sin\theta \tag{2}$$

$$a_{Az} = \ddot{z}_A + g\cos\theta = -r_A\dot{\theta}^2 + g\cos\theta \tag{3}$$

$$a_{Bx} = \ddot{x}_B + g\sin\theta = r_B\ddot{\theta} - g\sin\theta \tag{4}$$

$$a_{Bz} = \ddot{z}_B + g\cos\theta = -r_B\dot{\theta}^2 + g\cos\theta \tag{5}$$

where (a_{Ax} a_{Az}) and (a_{Bx}, a_{Bz}) are the accelerations in corresponding directions of the sensor-fixed frame $x_Ao_Az_A$ and $x_Bo_Bz_B$; (x_A, z_A) and (x_B, z_B) are the coordinates at positions A and B in the global frame, and θ is the rotational angular displacement of the rigid segment in the global frame *XOZ*.

Based on $(2)\cdot r_B-(4)\cdot r_A$ and $(3)\cdot r_B-(5)\cdot r_A$, the angular displacement equations are obtained:

$$\theta = \sin^{-1}\left(\frac{a_{Ax}r_B - a_{Bx}r_A}{g(r_A - r_B)}\right), \theta = \cos^{-1}\left(\frac{a_{Az}r_B - a_{Bz}r_A}{g(r_B - r_A)}\right) \tag{6}$$

Based on Eqs. (2)–(4) and Eqs. (3)–(5) the angular velocity and acceleration of the rigid segment are calculated as follows:

$$\dot{\theta}^2 = \frac{a_{Az} - a_{Bz}}{r_B - r_A} \tag{7}$$

$$\ddot{\theta} = \frac{a_{Ax} - a_{Bx}}{r_A - r_B} \tag{8}$$

where r_A, r_B can be measured from the pivot point to the positions A and B, and a_{Ax}, a_{Bx}, a_{Az}, a_{Bz} can be measured with accelerometers.

2.2. Calculation of the under limb segmental orientation

To identify the human segmental orientation in the body-fixed local coordinate system, the rotational angles of the right thigh were measured as an example, i.e., the relative attitude of the thigh compared with the pelvis in 3D space was analyzed by considering the hip joint as a ball joint, which permits rotations in three angular directions (flexion/extension, abduction/adduction and thigh inernal/external rotation directions).

The following systems of coordinates are introduced to explain the flexion/extension and abduction/adduction hip joint rotational angles as shown in Fig. 2:

1. *O*–*XYZ* is global frame with the axes *X*, *Y*, and *Z* pointing forward, outward and downward.
2. O_r–$X_rY_rZ_r$ is body-fixed local frame with the origin O_r at the hip joint. Suppose it maintains constant orientation in 3D space with the axes parallel to the axes of the global system. In the joint rotation convention for a hip joint (Zatsiorsky and Vladimir, 1998), Y_r axis describes the flexion/extension motion. X_r axis is used to measure abduction and adduction.
3. A–$x_Ay_Az_A$ and B–$x_By_Bz_B$ are the sensor coordinate systems for the two accelerometers which are attached to the thigh at positions A and B. The z_A axis is the long axis of the thigh segment (along the femur); the x_A axis is perpendicular to the z_A axis in the sagittal plane of the femur; the y_A axis is orthogonal to both axis x_A and z_A. The axes in o_B–$x_By_Bz_B$ have the same orientation with the axes in o_A–$x_Ay_Az_A$ correspondingly.

When the subjects perform straight-line walking trials, the origin O_r (the hip joint) of the local coordinate system is not fixed in the global frame. In this paper,