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Novel Approach for Lower Limb Segment Orientation in Gait Analysis Using Triaxial Accelerometers

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***Abstract* - This paper presents a novel approach only based on triaxial accelerometers for three-dimensional (3D) orientation of lower limb segment during real-time motion. With two coaxially placed triaxial accelerometers, the actual resultant acceleration signals containing the acceleration of gravity and lineal movement along each axis were obtained. The angle displacements for orientation of each segment were calculated based on low-pass filtered accelerometer signals without integration. To evaluate accuracy, two calculated angular displacements around *z, y* axes during different rotational conditions were obtained and compared with the result from a high-accuracy camera system. Only based on one kind of inertial sensor, triaxial accelerometers, the approach can be used to assess spatio-temporal gait parameters and evaluate movements of each segment of the lower limbs, and thus to objectively monitor gait function of patients in a clinical setting.**

***Index Terms* - novel approach, triaxial accelerometer, angular displacement, gait analysis**

I. INTRODUCTION

In the medical field, there is a need of small ambulatory sensor systems for measuring the kinematics of body segments. It is critical to detect the motion of certain segment of the lower limbs in biomechanical applications, especially in human gait analysis. Current methods for ambulatory measurement of body segment orientation have limitations on the volume, price, or accuracy. Optical motion analysis system is more precise but expensive and lab limited. Wearable sensor system comprised of accelerometers and gyroscopes is a new direction for the gait analysis, which has come into its own [1-4]. However, if you use an accelerometer to get the acceleration of human lower limbs, the resultant acceleration signal measured by an accelerometer is the vector sum of all the accelerations acting on the device along each sensitive axis. It is equals to the gravitational acceleration component plus the body segment linear acceleration component, without considering the effects of noises. The acceleration signals cannot be integrated simply to determine the velocity and displacement of the motion, due to the presence of the gravitational acceleration component and noises in the signal. Therefore, if you want to get the angle displacement of the motion with the equation $\theta=(180/\pi)\arcsin(a_z/g)$, the linear acceleration component must be neglected; else if you get the angle velocity of the body by a gyroscope, the angle displacement of the motion could be obtained by numerical integration, however, there was the integration drift that originates from errors in the angular velocity signal, in addition, the gyroscope offset must be continuously recalibrated and the orientation must be continuously corrected [1]. Reference [3] gives a method to solve the contradiction, getting the angle displacement with both accelerometer and gyroscope, and switching between the two sensors based on the wave frequency of the body segments. However, it is hard to give a satisfying switching frequency.

This paper presents a novel and simple method to estimate the orientation of the human body segments. That is to design a system with less kinds and quantities of sensors and without integration for ambulatory recording the real time orientation of lower limbs. The principle of the novel method was expatiated, the simulation was done and the details of the approach were discussed. And then, based on the theoretical research, a wearable device with two coaxially placed triaxial accelerometers was developed, interrelated experiments have been done to validate the feasibility of capturing the three-dimensional motion signals of the lower limb segment. With the data obtained from the sensors, two angle displacements θ_y, θ_z in spherical reference frame could be calculated. Compared with the data obtained from the high accuracy camera system, the method can be used in the gait analysis.

II. METHODS AND MATERIALS

A. *Explanation of the principle*

First, a rigid body was supposed rotated in the *X-Y-Z* coordinate system in the 3D space, as Fig.1 shows. The rotation angle along Y and Z axis are θ_y, θ_z, and a mark was taken on the rigid body as a reference point, the distance from the mark to origin is *r*.

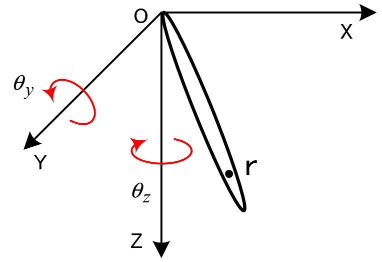

Fig.1 Motion of a rigid body in *X-Y-Z* reference frame

From Fig.1, the rotation acceleration matrix of the rigid body can be obtained without considering acceleration of gravity:

$$\mathbf{a}_r=\ddot{\mathbf{r}}=\begin{bmatrix}\ddot{\mathbf{x}}\\ \ddot{\mathbf{y}}\\ \ddot{\mathbf{z}}\end{bmatrix}=\begin{bmatrix}-r\dot{\theta}_y^{\,2}-r\dot{\theta}_z^{\,2}\\ r\ddot{\theta}_z\\ r\ddot{\theta}_y\end{bmatrix} \tag{1}$$

Then, if only the acceleration of gravity was considered, and

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the rigid body rotates along y axis at first, and then along z axis, the gravitational acceleration component along each sensitive axis is as follow:

$$\mathbf{a}_g = \begin{bmatrix} a_{gx} \\ a_{gy} \\ a_{gz} \end{bmatrix} = \begin{bmatrix} \cos\theta_z & \sin\theta_z & 0 \\ -\sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ 0 & 1 & 0 \\ \sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \mathbf{g} = \begin{bmatrix} -g\sin\theta_y\cos\theta_z \\ g\sin\theta_y\sin\theta_z \\ g\cos\theta_y \end{bmatrix} \tag{2}$$

In fact, the actual acceleration is a composition including accelerations of both gravity and rotation, without considering noises, which can be obtained as follow:

$$\mathbf{a} = \mathbf{a}_r + \mathbf{a}_g = \begin{bmatrix} -r\dot{\theta}_y^{\,2} - r\dot{\theta}_z^{\,2} \\ r\ddot{\theta}_z \\ r\ddot{\theta}_y \end{bmatrix} + \begin{bmatrix} -g\sin\theta_y\cos\theta_z \\ g\sin\theta_y\sin\theta_z \\ g\cos\theta_y \end{bmatrix} = \begin{bmatrix} -r\dot{\theta}_y^{\,2} - r\dot{\theta}_z^{\,2} - g\sin\theta_y\cos\theta_z \\ r\ddot{\theta}_z + g\sin\theta_y\sin\theta_z \\ r\ddot{\theta}_y + g\cos\theta_y \end{bmatrix} \tag{3}$$

Based on the resultant acceleration equation, each parameter is clear when the rigid body's rotating with acceleration of gravity in the three-dimensional reference frame. But how to evaluate the orientation of a rigid body or the real time angle displacement of a rigid body is the keystone. Suppose there is a rigid body with two triple axis accelerometers placed in the 3-D frame as the follow chart shows.

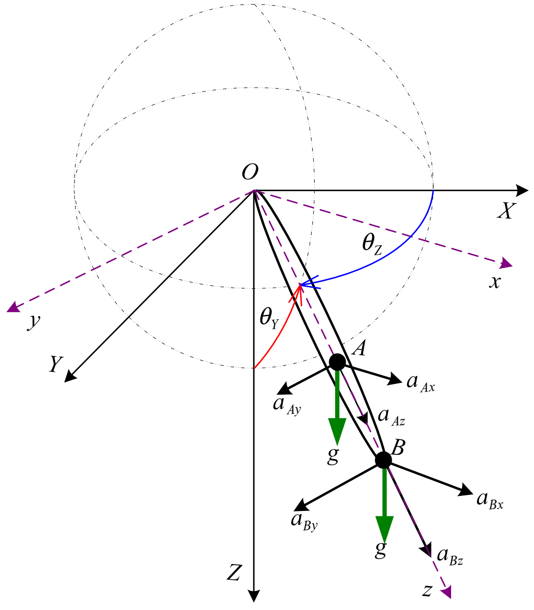

Fig. 2 Motion of a rigid body with two triaxial accelerometers in 3D reference frame

Two triple axis accelerometers were fixed coaxially on the rigid body where A and B were marked, and each axis of the accelerometers was in the same direction correspondingly, just as Fig.2 shows, then two groups of signals $\boldsymbol{a_A}$, $\boldsymbol{a_B}$ can be obtained as follow.

$$\mathbf{a}_A = \begin{bmatrix} a_{Ax} \\ a_{Ay} \\ a_{Az} \end{bmatrix} = \begin{bmatrix} -r_A\dot{\theta}_y^{\,2} - r_A\dot{\theta}_z^{\,2} - g\sin\theta_y\cos\theta_z \\ r_A\ddot{\theta}_z + g\sin\theta_y\sin\theta_z \\ r_A\ddot{\theta}_y + g\cos\theta_y \end{bmatrix} \tag{4}$$

$$\mathbf{a}_B = \begin{bmatrix} a_{Bx} \\ a_{By} \\ a_{Bz} \end{bmatrix} = \begin{bmatrix} -r_B\dot{\theta}_y^{\,2} - r_B\dot{\theta}_z^{\,2} - g\sin\theta_y\cos\theta_z \\ r_B\ddot{\theta}_z + g\sin\theta_y\sin\theta_z \\ r_B\ddot{\theta}_y + g\cos\theta_y \end{bmatrix} \tag{5}$$

$\boldsymbol{a_A}$, $\boldsymbol{a_B}$ are the actual compositions of the acceleration on each axis of x, y, z measured by the two triple axis accelerometers at location **A** and **B**, which can be used as known parameters, then angle placements θ_y, θ_z can be obtained by solving the equations set of (4) and (5).

$$\theta_y = \sin^{-1}\left(\frac{\pm\sqrt{(a_{Ax}r_B - a_{Bx}r_A)^2 + (a_{Ay}r_B - a_{By}r_A)^2}}{g(r_B - r_A)} \right) \tag{6}$$

$$\theta_y = \cos^{-1}\left(\frac{a_{Az}r_B - a_{Bz}r_A}{g(r_B - r_A)} \right) \tag{7}$$

$$\theta_z = \sin^{-1}\left(\frac{a_{Ay}r_B - a_{By}r_A}{g(r_B - r_A)\sin\theta_y} \right) \tag{8}$$

$$\theta_z = \cos^{-1}\left(\frac{a_{Ax}r_B - a_{Bx}r_A}{-g(r_B - r_A)\sin\theta_y} \right) \tag{9}$$

Angle velocities and accelerations also can be obtained as following equations shows:

$$a_{Ax} - a_{Bx} = (r_B - r_A)(\dot{\theta}_y^{\,2} + \dot{\theta}_z^{\,2}) \tag{10}$$

$$a_{Ay} - a_{By} = (r_A - r_B)\ddot{\theta}_z \tag{11}$$

$$a_{Az} - a_{Bz} = (r_A - r_B)\ddot{\theta}_y \tag{12}$$

B. Simulation and analysis

As (6-9) show, angle displacements in two directions can be obtained on the basic of a series of accelerations. Then, simulations based on the above presented approach would be done, showing the feasibility of it. In the simulation, a_{Ax}, a_{Ay}, a_{Az}, a_{Bx}, a_{By}, a_{Bz} are given signals, r_A, r_B are constant.

In Fig.3, the curves show the angle placement θ_y, θ_z calculated by the functions of arc sine and arc cosine in half a motion cycle, and there are random noises acting on the accelerations of each axis. As the curves of the errors shown, when the angle displacement is close to 0°, errors of the calculated result by arc cosine are much bigger than the one calculated by arc sine. And compared with the situation when the angle displacement is close to 90°, the errors obtained from arc cosine are much bigger than arc sine. Because the linearity of arc sine is much better than arc cosine when the angle is closed to 0°, which is opposite to the situation when the angle is closed to 90°. Therefore, in order to gain a higher precision of angle placement, a switching method can be introduced, that is when the absolute value of the angle displacement is between 0 and 30°, the arc sine is adopted as a calculating function, between 30 °and 90 ° arc cosine is used.

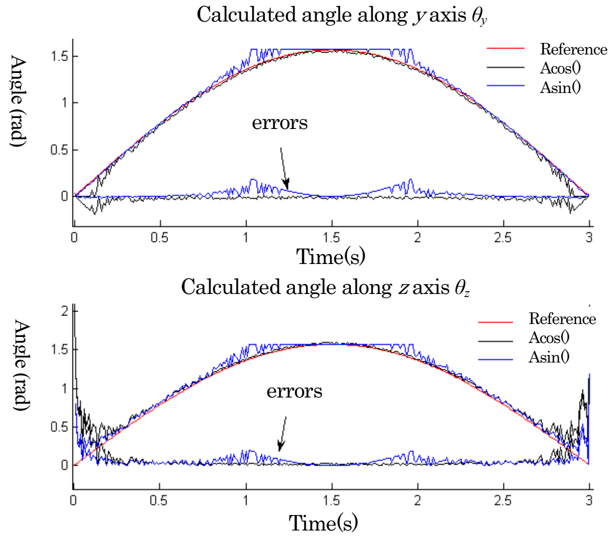

Fig. 3 Angle placement calculated by inverse trigonometric function in half a motion cycle

What's more, it can be seen in Fig. 3, the curve of θ_z in the second chart fluctuates more intensively than the curve of θ_y in the first chart when the absolute value of the angle displacement is closed to 0°. The reason is that the calculation equation(8)(9) of θ_z contains $sin\theta_y$, which has had some errors already with noises added in, that is to say, the calculated result of θ_z has included the errors from θ_y, and it had been magnified. However, in Fig.3, in order to show the above mentioned problem, the amplitude of the random noise is a little bigger. The following charts will show the calculated angle displacements θ_y, θ_z based on the given accelerations along each axis of the two coaxially placed accelerometers with noises, and the boundary angle for alternating the calculating function is $k\pi\pm30°$ (k=0,1,2…).

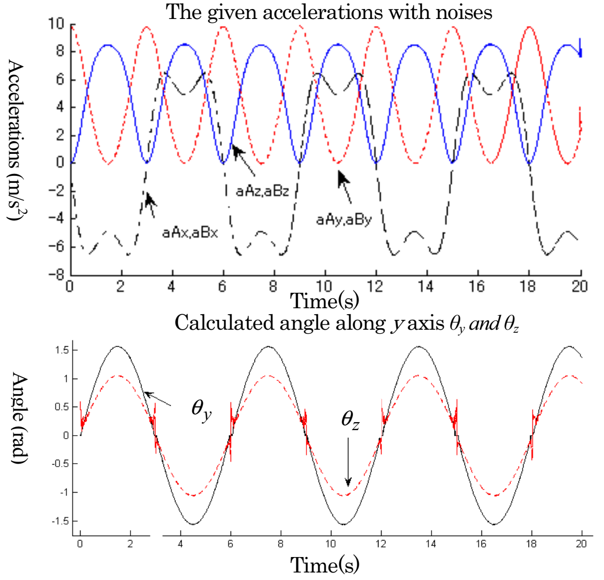

Fig.4 Given accelerations and the corresponding angle of θ_y, θ_z with noises

C. Experiment

In order to validate the feasibility of the above arithmetic, firstly, consider a simple condition, with the two groups of 3-axes accelerations, the main rotation angle along y axis was calculated. Then a simply device with two triaxial accelerometer based chips (MM-2860) was developed. And the PCI-6071E DAQ device was used to pick up the analogue signals and transform them to digital signals to the PC. At the same time, Carbon Composition Potentiometers (RV30YN20S-B504) was fixed in the rotation axis of the board, therefore, the rotational angle displacement of the board with the Carbon Composition Potentiometers can be obtained directly to do comparison with the calculated angle displacement with measured accelerations by the two triaxial accelerometer based chips. With the simple device, a group signal of simulating actual shank swing was obtained for the angle calculation. The Fig.5 shows the structure of the simple device.

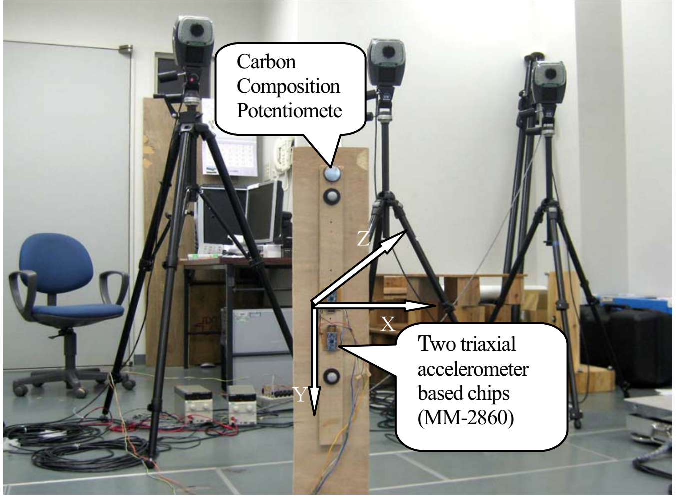

Fig.5 A simple device based on two MM-2860 chips

In order to validate the feasibility of the above arithmetic further, especially the feasibility in gait analysis, a wearable and removable elementary system was developed. Two triaxial accelerometer based chips (MM-2860) and one MCU (H8/3694) were adopted in the system for the gait analysis.

The following picture shows the experiment with the accelerometer based system on the shank segment of the lower limb. There are two marks on the shank for the high-accuracy camera system, to capture the velocities and accelerations of the two positions, then to calculate the orientation of the shank. In order to validate the usability of the developed system, we supposed a simple situation first, that is the shank waves only simulate the rotation of the former board device. The picture shows one wave circle of left shank wearing the developed wearable system.

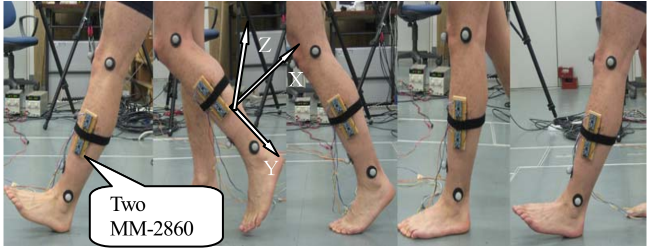

Fig.6 Shank movement with the developed device

III. RESULTS

The following charts show the six accelerations along each axis of the two accelerometers and the corresponding calculated angles θ_y, θ_z. In order to compare the angles calculated from the accelerations and obtained from the high-accuracy camera system, both of the angles are included in the same chart.

The data obtained from the sensors was voltage signal, and then it was translated into actual accelerations. As the Fig.7 shows, the final orientation angle θ_y using the filter is compared with the data from Carbon Composition Potentiometers (RV30YN20S-B504). And Fig.8 shows the data from the wearable system, the calculated angles from the sensor based data are compared with the high-accuracy camera system. It can be seen that the orientation error based on the actual data is a little bigger, especially the resultant angle along the z axis in Fig.8. Because it contains the accelerator drift, and in the experiment, the axes of the two sensors cannot be coaxially placed exactly as in the theory, and it is hard to fix the device on the shank segment as fix it on a rigid body firmly, because the muscle and skin of the lower limb is moving and vibrating according to the motion of the body segments, therefore there must be some instability errors. It is compulsory to get rid of or reduce the influence of uncertainty factors in the future experiments.

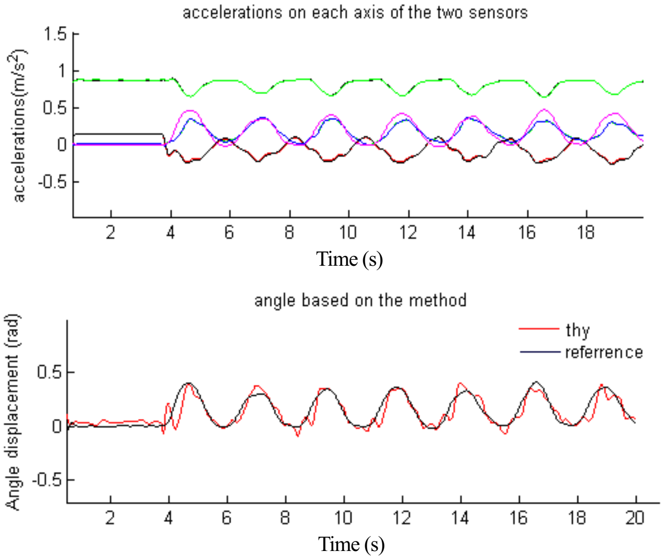

Fig.7 Experiment data from the simple device

What's more, as is seen in the former equations, the dispersion between r_A and r_B is a part of denominator in each equation, so a small error of the dispersion r_B-r_A can cause a bigger error in the calculated angles. And in the former section, we have discussed the error of θ_z, it contains the errors of θ_y, so it must be a little inaccurate compared with θ_y, that's why the curve in the three chart of Fig.8 has more errors.

From the experiment data, it can be found that there is a clear relationship between measured acceleration signals and the calculated angles when the two coaxially placed triaxial accelerometers were located at different positions, and the errors varied according to the distance between the two sensors. With the analysis of the signals between the developed device and the high-accuracy camera system, the novel method present in the paper is feasible in actual measurement.

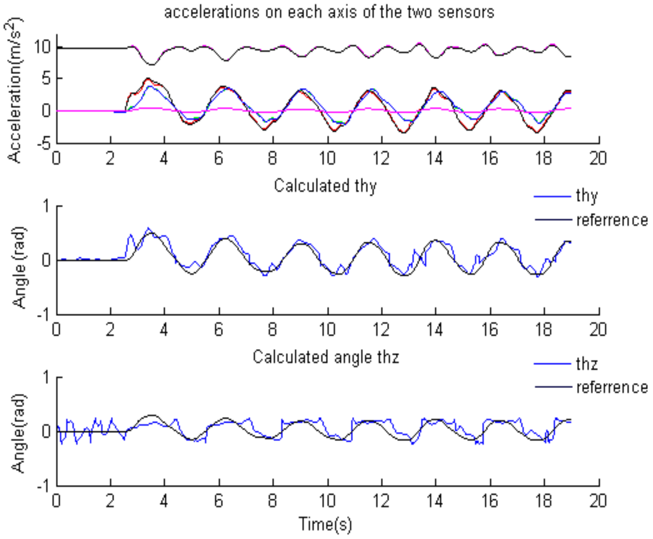

Fig.8 Experiment data from the developed wearable system

IV. DISCUSSION

To recognize the orientation of human body segment, how the angle displacement changes along each axis is the most important. As is shown in the (6-9), a_{Ax}, a_{Ay}, a_{Az}, a_{Bx}, a_{By}, a_{Bz} are the overall accelerations along each sensitive axis, including accelerations of gravity, motion and noises, which can be measured by the sensors and used to calculate angle displacements as known quantities. r_A and r_B are the distances from each accelerometer to the origin, which depends on the position where the sensors were fixed. However, in the actual experiment, the acceleration signals and the distance are measured quantities, which must contain noises and errors, what's more, the scale of r_A, r_B will also affect the precision of the calculated result of the angle displacement θ_y, θ_z, especially when the developed device was worn on the lower limb, the precision of measuring the distance is very important. Therefore, it is necessary to filtrate the signals by a low-pass filter and do a more accurately measurement of r_A, r_B.

As the accelerometers rotating in the gravitational field, the resultant accelerations measured by an accelerometer are the vector sum of all of the accelerations acting on the device along the sensitive axis, including acceleration of gravity, acceleration of motion and rotation, and noises. In this paper, in order to explicate the novel approach and validate the it with a wearable sensor system, the rigid body only swings around the vertical direction below the horizontal plane, the gravitational acceleration component along the z axis changes from 0g to +1g, in other words, the rotation angle about Y, Z axis is no bigger than 90°. What's more, human gait contains a substantial translation movement, that is to say, the rotation of the segment cannot be adequately modeled by a simple rotation rigid model but contains movement with the trunk. And when the two triaxial accelerometers were fixed, each axis of them must be in the same direction and line, to reduce the errors. Therefore, how to enlarge the investigable moving range of the body segments and the precision of the device when it is used for actual measurement need more work in the future.

V. CONCLUSION

A novel approach for real time recording of human body segment orientation was presented, based on the 3D acceleration only, without adopting integration to get the 3D angle displacement of the rotating segment in the gravitational field. Then, based on the analysis of the experiment data, compared with the data obtained from the high-accuracy camera system, the feasibility of the novel method was validated, and it can be adapted to assess the accelerations on the segment of the low limbs, estimating the spatio-temporal gait parameters in human gait analysis. With simple calculations and fewer kinds and quantities of sensors, a precise angle displacement can be acquired. It is feasible to only use triaxial accelerometers based device for studying the gait during routine daily activities of patients or persons needing health evaluation by gait analysis.

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