A Method for the Reduction of Skin Marker Artifacts During Walking : Application to the Knee

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Previous studies have demonstrated the importance of joint angle errors mainly due to skin artifact and measurement errors during gait analysis. Joint angle errors lead to unreliable kinematics and kinetic analyses in the investigation of human motion. The purpose of this paper is to present the Joint Averaging Coordinate System (JACS) method for human gait analysis. The JACS method is based on the concept of statistical data reduction of anatomically referenced marker data. Since markers are not attached to rigid bodies, different marker combinations lead to slightly different predictions of joint angles. These different combinations can be averaged in order to provide a "best" estimate of joint angle. Results of a gait analysis are presented using clinically meaningful terminology to provide better communication with clinical personal. In order to verify the developed JACS method, a simple three-dimensional knee joint contact model was developed, employing an absolute coordinate system without using any kinematics constraint in which thigh and shank segments can be derived independently. In the experimental data recovery, the separation and penetration distance of the knee joint is supposed to be zero during one gait cycle if there are no errors in the experimental data. Using the JACS method, the separation and penetration error was reduced compared to well-developed existing methods such as ACRS and Spoor & Veldpaus method. The separation and penetration distance ranged up to 15 mm and 12 mm using the Spoor & Veldpaus and ACRS method, respectively, compared to 9 mm using JACS method. Statistical methods like the JACS can be applied in conjunction with existing techniques that reduce systematic errors in marker location, leading to an improved assessment of human gait.

Key Words : Gait Analysis, Experimental Error, Skin Artifact, Knee Joint, Human Motion, Kinematics

1. Introduction

During the past decade, efforts to achieve accurate kinematic data in human motion analysis have progressed to understanding human joint function. Measured kinematic data is the major input source to conduct kinematic analysis. The accuracy of the model is directly related to the accuracy of the experimentally measured data. However, the common gait analysis experimental method, using a commercial optical tracking system, has accuracy limitations due to skin movement relative to the underlying skeletal structure while in motion, due to deformation of skeletal structure and due to the resolution error of the tracking system (Cappozzo et al., 1996).

In clinical gait analysis, anatomical skin markers are generally employed to assess a patient's joint function and movement capabilities during pre- or post-rehabilitation (Bogert et al., 1990 ;

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Kadaba et al., 1990 ; Lu and O'Connor, 1999; Reinschmidt et al., 1997). In the most widely applied method, three markers are used for each body segment, with motion analysis hardware and software reducing the marker position data to body segment location and orientation (Allard et al., 1995 ; Voughan et al., 1992). During gait analysis it is impossible to achieve error-free position kinematic data because of skin movement, skeletal deformation and equipment errors (Cappello et al., 1997 ; Cappozzo et al., 1996 ; Crawford et al., 1996 ; Lucchetti et al., 1998 ; Reinschmidt et al., 1997a). In order to improve the accuracy of the gait data, both experimental methods (Kadaba et al., 1990 ; Reinschmidt et al., 1997b) and numerical methods (Cheze et al., 1995 ; Lu and O'Connor, 1999 ; Spoor and Veldpaus, 1980) have been reported in previous studies.

The method used by Spoor and Veldpaus (1980) determines the moment of inertia of the markers about their average position at specific intervals during the gait cycle. The principle axes of the marker inertia are then calculated as an eigenvalue problem. For a system based on three non-colinear markers, the two non-zero eigenvectors are the principle axes, and lie in the plane containing the three markers. The third rotational axis is taken as the cross-product of the first two. The method minimizes the influence of noise by making use of the shape distribution of the marker points, rather than their values. Cheze et. al, (1995) developed a solidification procedure, based on the work of Spoor and Veldpaus (1980), to reduce experimental error, mainly due to skin movement, by optimizing the coordinate reference system over the whole gait cycle. Given a redundant number of markers, fixed on a single body segment, three markers which best represent the least perturbed triangle over the range of motion were chosen using an iterative search and elimination procedure.

Averaging techniques have frequently been used to recover better estimates of body segment orientation. These techniques involve averaging either the Euler-Bryant angles, or averaging of test trials. Orientation recovery, using Euler angle methods, depends on the sequence of the three rotations. Given three non-collinear anatomical markers, there exist six possible Euler angle rotational sequence permutations. Panjabi et al., (1993) and Oxland et al., (1992) averaged the results of these six possible permutations. This method has a theoretical problem since the values of the Euler angle rotations are dependent upon the sequence in which they were determined and they should not be directly added or averaged. Reinschmidt et al. (1997a and 1997b) used trial averaging when comparing the use of skin markers to bone pin markers for the recovery of knee motion during gait and running. These trial averaging techniques include errors due to subject's different walking speed, path and pattern for each trial.

In order to overcome limitations of these methods, Mun et al., (1999a ; 1999b ; 2001) suggested the Averaged Coordinate Reference System (ACRS) method. Even though rigid body assumptions are normally employed for kinematic and kinetic analysis in the biomechanics field, real experimental human motion data reflects deformable body motions. The ACRS concept was developed based on this fact. Like the Joint Averaging Coordinate System (JACS) method presented in this paper, the ACRS method averages multiple coordinate reference systems determined from the skin markers, using one gait trial test. It can be applied to experimental gait trials using three or more markers. In the ACRS method, each skin marker was treated as the origin of a local coordinate system for its body segment. By selecting one marker combination as the reference configuration, a series of constant transformation matrices can be determined from calibration data between all other marker combinations and the reference configuration. By applying these rotation matrices to the recovered direction cosine vectors at each marker location during the gait test, the Euler angles for the segment orientation were computed and then averaged to get statistically better results. This method differs from the previously mentioned Euler angle averaging techniques, because the rotational sequence used for each permutation is the same and thus there are no theoretical problems with averaging the resultant angles.

The major difference between the ACRS and JACS methods is that the ACRS method averages the orientation of a body segment, while the JACS method averages the relative orientation of the knee joint. The method presents the relative motion between the femur and tibia in terms of the Grood and Suntay (1983) coordinate system. This coordinate system represents three-dimensional rotations using a clinical description such as flexion/extension, adduction/abduction and external/internal rotations.

The objective of this study is to show the effectiveness of the JACS method when a five-marker system is employed for experimental gait analysis. In order to verify the effectiveness of the developed JACS method, a comparison with a well-defined existing method such as Spoor & Veldpaus and ACRS method (Mun, 2001) using multiple markers from redundant marker sets is made.

2. Analysis

Use of three non-collinear skin markers is the most generally applied experimental method in gait analysis. Three markers are the minimum requirement for decomposing the three-dimensional kinematics of the body segment. Detailed mathematical equations for the experimental data reduction procedure, including the transformation matrix calculation, have appeared in previous publication (Vaughan et al., 1992).

2.1 Joint averaging coordinate system (JACS)

In order to describe the relative segmental motion between femur and tibia in clinical terminology, we adopted the Grood and Suntay [8] joint reference frame, as shown in the Fig. 1. In the figure, x_t', y_t' and z_t' represent the body fixed local coordinate system of the thigh while x_s', y_s' and z_s' represent the local coordinate system of the shank segment. This coordinate reference frame provides a clinical description of three-dimensional flexion/extension, abduction/adduction and external/internal rotations, and translations such as lateral tibial displacement, anterior tibial drawer displacement and joint distractions. In this paper, we restrict the presentation of the JACS method to knee joint rotations, however extension of the method to include the translations is straightforward.

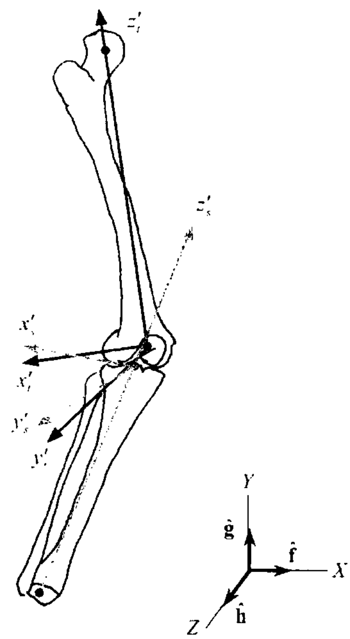

Fig. 1 Grood and Suntay's anatomical coordinate system

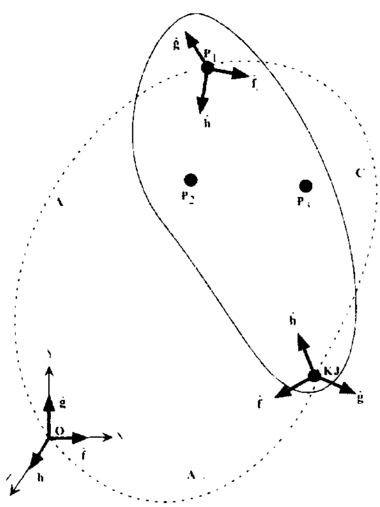

Fig. 2 Configuration of the local transformation for three-markers system

Given three non-collinear points, $\mathbf{P}_1$, $\mathbf{P}_2$ and $\mathbf{P}_3$, on a body segment, as shown in Fig. 2, the orientation of the body segment reference frame, using point $\mathbf{P}_1$ as the origin, can be determined with respect to global reference frame by a transformation matrix $\mathbf{A}_i$ expressed as

$$\mathbf{A}_i=\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}=[\hat{\mathbf{f}}_i \quad \hat{\mathbf{g}}_i \quad \hat{\mathbf{h}}_i] \tag{1}$$

where $\hat{\mathbf{f}}_i$, $\hat{\mathbf{g}}_i$ and $\hat{\mathbf{h}}_i$ are orthogonal unit vectors. Based on an assumption of rigid body kinematics, a constant transformation matrix, $\mathbf{C}_i$, exists between the body segment reference frame and the Grood and Suntay joint reference frame on the body segment. This transformation can be determined from the human subject's standing calibration position of the experimental gait trial. Taking, $\mathbf{A}_{GS}$, as the transformation matrix from the Grood and Suntay reference frame to the global coordinate reference system the transformation matrix $\mathbf{C}_i$ can be calculated as

$$\mathbf{C}_i=\mathbf{A}_i^{-1}\mathbf{A}_{GS}=\mathbf{A}_i^T\mathbf{A}_{GS} \tag{2}$$

where $\mathbf{A}_i^{-1}=\mathbf{A}_i^S$ because the transformation matrices are orthonormal. Procedures for calculating the transformation matrices have been given in previous publications (Allard et al., 1995 ; Vaughan et al., 1992).

Changing the origin of the body segment reference frame to each of the three marker locations, $\mathbf{P}_1$, $\mathbf{P}_2$ and $\mathbf{P}_3$, six permutations of the transformation matrix, $\mathbf{A}_i$, can be obtained. However three of the permutations differ by a rotation of 180° about the axis perpendicular to the plane formed by the markers. Thus, only three permutations are truly unique. As shown in Fig. 3, each marker is used as the origin of a local reference frame, cyclically permuted from location $\mathbf{P}_1$ to $\mathbf{P}_3$. The order of each combination changes, with the first combination using the marker locations in the order $\mathbf{P}_1\mathbf{P}_3\mathbf{P}_2$, the second combination using the order $\mathbf{P}_2\mathbf{P}_1\mathbf{P}_3$, and the final combination using the order $\mathbf{P}_3\mathbf{P}_2\mathbf{P}_1$. Using Eq. (2), three different constant transformations, $\mathbf{C}_1$, $\mathbf{C}_2$, and $\mathbf{C}_3$, corresponding to each of the three marker combination permutations, can be obtained between the

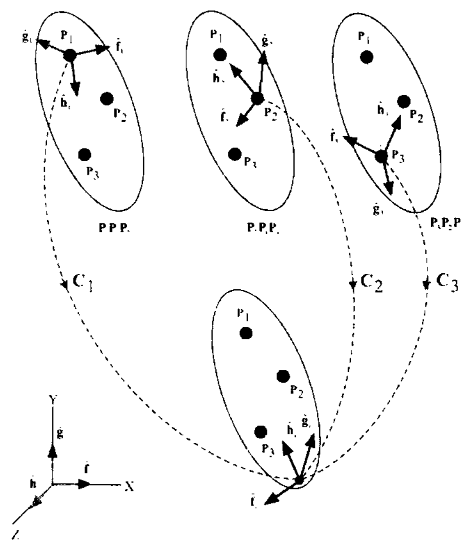

Fig. 3 Permutations and transformations of three marker system

respective body reference frames and the Grood and Suntay reference frame at the standing calibration position. If a redundant marker system is used, such as a four or five marker system, a total of twelve or thirty transformation matrix permutations, respectively, are possible without including the mirror-image combinations.

During each frame of the experimental gait trials, permutations of the Grood and Suntay transformation matrices, $\mathbf{A}_{GSi}$, for the body segment can be calculated as

$$\mathbf{A}_{GSi}=\mathbf{A}_i\mathbf{C}_i \tag{3}$$

where $\mathbf{A}_i$ is the transformation matrix between the global reference coordinate system and the local body segment coordinate system for the i^{th} marker permutation, and $\mathbf{C}_i$ is the corresponding constant transformation matrix calculated from the standing calibration position. Once $\mathbf{A}_{GSi}$ is calculated, angles representing the segment orientation θ_{xi}, θ_{yi}, and θ_{zi}, can be obtained as Bryant angle rotations using the consistent $R_xR_yR_z$ convention. If the motion of the body segment, and its associated skin markers, followed the rigid body assumption, the recovered rotation angles for each of the marker permutations would be identical. However, non-rigid body motion, mainly due to movement of the markers on the skin, leads to slightly different values for each of the recovered body segment orientation angles. In the JACS method, each of the three body segment orientation angles, are averaged, as

$$\bar{\theta}_x=\frac{1}{N}\sum_{i=1}^{N}\theta_{xi} \tag{4}$$

$$\bar{\theta}_y=\frac{1}{N}\sum_{i=1}^{N}\theta_{yi} \tag{5}$$

$$\bar{\theta}_z=\frac{1}{N}\sum_{i=1}^{N}\theta_{zi} \tag{6}$$

where N represents the total number of marker combination permutations. Averaging by this method reduces experimental error in a statistical sense (Figliola and Beasley, 1995). The method differs as compared to previously Euler-Bryant angle averaging techniques (Oxland et al., 1992 ; Panjabi et al., 1993), since the JACS method uses consistence rotation sequences for every marker combination permutation. The previous techniques used only a single marker combination, and averaged the results of the six possible Euler-Bryant angle rotational sequences ; $R_xR_yR_z$, $R_yR_zR_x$, $R_zR_xR_y$, $R_yR_xR_z$, and $R_zR_yR_x$, which is theoretically unsound.

Once permutations of the Grood and Suntay transformation matrices for the thigh and Shank, $\mathbf{A}_{GSi}^{Thigh}$ and $\mathbf{A}_{GSi}^{Shank}$, are calculated using Eq. (3), the each of the relative angles, $\mathbf{B}_i$ between the thigh and shank body segment can be determined as

$$\mathbf{B}_i=(\mathbf{A}_{GSi}^{Shank})^{-1}\mathbf{A}_{GSi}^{Thigh}=(\mathbf{A}_{GSi}^{Shank})^{T}\mathbf{A}_{GSi}^{Thigh} \tag{1}$$

where $(\mathbf{A}_{GSi}^{Shank})^{-1}=(\mathbf{A}_{GSi}^{Shank})^{T}$ because the transformation matrix is orthogonal.

Translation and rotation of three-dimensional rigid body motion can be calculated using three non-collinear markers on a body. In Fig. 4, the points $\mathbf{P}_1$ through $\mathbf{P}_3$ represent three markers attached to the body segment. In this specific example, $\mathbf{P}_1$ is used as the origin of the local coordinate system on the body. Two vectors, $\mathbf{v}_1$ and $\mathbf{v}_2$, which lie in the plane formed by the markers, point from $\mathbf{P}_1$ to $\mathbf{P}_2$ and $\mathbf{P}_3$ as

$$\mathbf{v}_1=\mathbf{P}_2-\mathbf{P}_1 \tag{8}$$

$$\mathbf{v}_2=\mathbf{P}_3-\mathbf{P}_1 \tag{9}$$

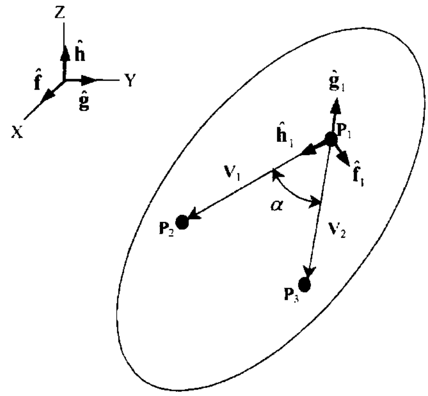

Fig. 4 Configuration of the three marker system

Unit vectors, $\hat{\mathbf{v}}_1$ and $\hat{\mathbf{v}}_2$, which point in the directions $\mathbf{v}_1$ and $\mathbf{v}_2$, respectively, can be calculated as

$$\hat{\mathbf{v}}_1=\frac{\mathbf{v}_1}{\|\mathbf{v}_1\|} \tag{10}$$

$$\hat{\mathbf{v}}_2=\frac{\mathbf{v}_2}{\|\mathbf{v}_2\|} \tag{11}$$

In the Fig. 4, is shown as the angle between the two unit vectors and and the cosine of can be calculated using the dot product as

$$\hat{\mathbf{v}}_1\cdot\hat{\mathbf{v}}_2=\|\hat{\mathbf{v}}_1\|\,\|\hat{\mathbf{v}}_2\|\cos\alpha=\cos\alpha \tag{12}$$

2.2 Spoor and Veldpaus' method (Spoor and Veldpaus, 1980)

This method is based on the least square concept which minimizes the influence of noise by making use of the shape distribution of the marker points, rather than their values. The objective function can be written as

$$f(\mathbf{v},\mathbf{R})=\frac{1}{n}\sum_{i=1}^{n}(\mathbf{R}\mathbf{a}_i+\mathbf{v}-\mathbf{p}_i)^T(\mathbf{R}\mathbf{a}_i+\mathbf{v}-\mathbf{p}_i) \tag{13}$$

$$\mathbf{R}^T\mathbf{R}=\mathbf{I} \tag{14}$$

where $\mathbf{v}$ is transformation vector and $\mathbf{R}$ is rotation matrix describing the movement of a rigid body from a position 1 into another position 2. $\mathbf{R}^T\mathbf{R}=\mathbf{I}$ because the transformation matrices are orthogoranl where $\mathbf{I}$ is the 3×3 unit matrix, and $\mathbf{a}_i$ and $\mathbf{p}_i$ denote the measured radius vectors of n non-collinear points of the body in position 1 and in position 2, respectively. In our analysis, n is five for thigh segment and three for shank segment.

The exact vector of body position 2 can be described as

$$\mathbf{q}_i=\mathbf{R}\mathbf{a}_i+\mathbf{v} \tag{15}$$

where $\mathbf{R}$ and $\mathbf{v}$ are unknown and must be determined from the measured radius vectors in position 2. The application of the method uses the Lagrangian multiplier technique to determine the rotation matrix $\mathbf{R}$ and the transformation matrix $\mathbf{v}$ that minimize Eq. (13) with the constraint Eq. (14), which leads to the solution of eigenvalues and eigenvectors of matrix $\mathbf{A}$.

$$\mathbf{A}=\mathbf{M}^T\mathbf{M} \tag{16}$$

where

$$\mathbf{M}=\frac{1}{n}\sum_{i=1}^{n}(\mathbf{p}_i\mathbf{a}_i^T)-\mathbf{p}\mathbf{a}^T \tag{17}$$

where $\mathbf{a}$ and $\mathbf{p}$ are average vector described as

$$\mathbf{a}=\frac{1}{n}\sum_{i=1}^{n}\mathbf{a}_i \tag{18}$$

$$\mathbf{p}=\frac{1}{n}\sum_{i=1}^{n}\mathbf{p}_i \tag{19}$$

The eigenvalues (D_{ii}) and eigenvectors ($\mathbf{W}$) of Eq. (16) can be calculated from

$$(\mathbf{A}-\lambda\mathbf{I})\mathbf{x}=0 \tag{20}$$

By denoting

$$\mathbf{MW}=(\mathbf{m}_1\quad \mathbf{m}_2\quad \mathbf{m}_3) \tag{21}$$

the rotation matrix $\mathbf{R}$ can be determined if and only if at least two of the eigenvalues $D_{11}\geq D_{22}\geq D_{33}$ differ significantly from zero as

$$\mathbf{R}=\left(\frac{1}{D_{11}}\mathbf{m}_1\quad \frac{1}{D_{22}}\mathbf{m}_2\quad \frac{1}{D_{11}\cdot D_{22}}\mathbf{m}_1\times\mathbf{m}_2\right) \tag{22}$$

Thus, the transformation vector from the position 1 to position 2 can be determined as

$$\mathbf{v}=\mathbf{p}-\mathbf{R}\mathbf{a} \tag{23}$$

2.3 Verification of JACS method

In order to verify the developed JACS method, a simple 3-D knee joint contact model was developed, employing an absolute coordinate system. The lateral and medical condyles were assumed spherical having fixed radii of 20.4 mm and 19.9mm, respectively (Kurosawa et al., 1985). Four possible contacts such as one point contact, two point contact, separation and penetration is allowed in the six degree-of-freedom knee joint computational model. The schematic plot of the contact of knee model is given in Fig. 5. In the figure, the center of two spheres, $\mathbf{P}_{11}$ and $\mathbf{P}_{12}$ can be expressed in terms of the global Cartesian reference coordinate system as

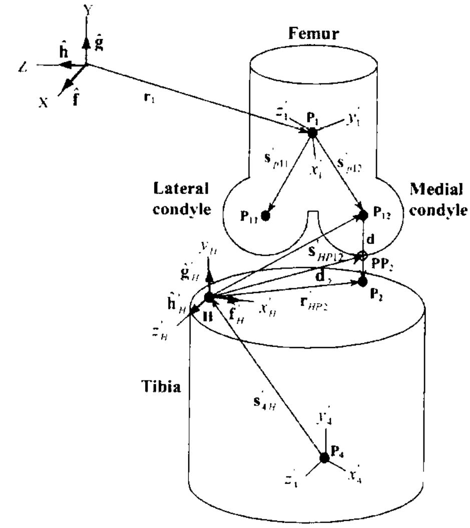

Fig. 5 Configuration of knee joint contact modeling

$$\mathbf{P}_{11}=\mathbf{r}_1+\mathbf{A}_1\mathbf{s}'_{p11} \tag{24}$$

$$\mathbf{P}_{12}=\mathbf{r}_1+\mathbf{A}_1\mathbf{s}'_{p12} \tag{25}$$

In the Eqs. (13) and (14), $\mathbf{r}_1$ is the vector from the origin of the global laboratory reference to the local origin of femur segment and $\mathbf{A}_1$ is the transformation matrices from the local coordinate system of the femur to the global coordinated system during the motion. The constant local vector $\mathbf{s}'_{p11}$ and $\mathbf{s}'_{p12}$ are calculated from the standing calibration stage data as

$$\mathbf{s}'_{p11}=\mathbf{A}_{1S}^{-1}(\mathbf{r}_1-\mathbf{P}_{11}) \tag{26}$$

$$\mathbf{s}'_{p12}=\mathbf{A}_{1S}^{-1}(\mathbf{r}_1-\mathbf{P}_{12}) \tag{27}$$

where, $\mathbf{A}_{1S}^{-1}$ is the inverse matrix of the transformation matrix $\mathbf{A}_{1S}$ calculated at the standing data set. In the development of the following equations, the medial condyle and tibia plateau will be considered as the example. Development of the lateral condyle side equations is the same as the medial condyle case equations.

An arbitrary point, $\mathbf{H}$, placed on the tibia surface can be expressed as

$$\mathbf{H}=\mathbf{r}_4+\mathbf{A}_2\mathbf{s}'_{4H} \tag{28}$$

where, $\mathbf{s}'_{4H}$ is constant vector given in the segment's local coordinate system. This vector can be calculated at the standing calibration stage as

$$\mathbf{s}'_{4H}=\mathbf{A}_{2s}^{-1}(\mathbf{r}_4-\mathbf{H}) \tag{29}$$

where, $\mathbf{A}_{2s}^{-1}$ is the inverse matrix of the transformation matrix $\mathbf{A}_{2s}$ calculated at the standing position. The calculation procedure of the contact point of the medial condyle on the tibia plateau, $\mathbf{P}_2$, follows. The contact point $\mathbf{P}_2$ can be expressed in terms of global Cartesian coordinate system as

$$\mathbf{P}_2=\mathbf{H}+\mathbf{A}_2\mathbf{C}'_O\begin{Bmatrix} a \\ 0 \\ c \end{Bmatrix} \tag{30}$$

$$\mathbf{C}'_O=\mathbf{A}_{2s}^{-1} \tag{31}$$

where, C'_O is the constant transformation matrix between IRED number 4 and position $\mathbf{H}$ at the standing calibration stage. The scalar values, a and c, are the distance from position $\mathbf{H}$ to the contact point $\mathbf{P}_2$ in terms of local coordinate system of x'_H, y'_H and z'_H. The geometric compatibility condition is that the vector $\mathbf{d}$ has to be perpendicular to the unit vectors $\hat{\mathbf{f}}$ and $\hat{\mathbf{g}}$ to satisfy the contact condition. Thus, the dot product equations can be written as

$$\mathbf{d}\cdot\hat{\mathbf{f}}=\mathbf{d}\cdot\mathbf{A}_2\mathbf{C}'_O\hat{\mathbf{f}}'_H=0 \tag{32}$$

$$\mathbf{d}\cdot\hat{\mathbf{h}}=\mathbf{d}\cdot\mathbf{A}_2\mathbf{C}'_O\hat{\mathbf{h}}'_H=0 \tag{33}$$

And, the scalar distances a and c can be determined as

$$a=\hat{\mathbf{f}}(\mathbf{P}_1-\mathbf{H})=\hat{\mathbf{f}}^T\mathbf{A}_2\mathbf{C}'_O\begin{Bmatrix} a \\ 0 \\ c \end{Bmatrix}=\begin{Bmatrix} 1 \\ 0 \\ 0 \end{Bmatrix}\mathbf{C}_O^T\mathbf{A}_2^T\mathbf{A}_2\mathbf{C}'_O\begin{Bmatrix} a \\ 0 \\ c \end{Bmatrix} \tag{34}$$

$$c=\hat{\mathbf{h}}(\mathbf{P}_1-\mathbf{H})=\hat{\mathbf{h}}^T\mathbf{A}_2\mathbf{C}'_O\begin{Bmatrix} a \\ 0 \\ c \end{Bmatrix}=\begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix}\mathbf{C}_O^T\mathbf{A}_2^T\mathbf{A}_2\mathbf{C}'_O\begin{Bmatrix} a \\ 0 \\ c \end{Bmatrix} \tag{35}$$

Since separation and penetration is allowed in the computational knee joint model, there exist two contact points for medial condyle such as $\mathbf{P}_2$ and $\mathbf{PP}_2$ while in motion. Thus, the distance between those points is directly affected for the calculation of internal reaction force of knee joint.

$$\text{distance}=\hat{\mathbf{g}}'^T_H\mathbf{d}_2 \tag{36}$$

$$\hat{\mathbf{g}}'_H=\hat{\mathbf{h}}'_H\times\hat{\mathbf{f}}'_H \tag{37}$$

2.3 Experiment using redundant marker system

Experimental gait data from a normal, healthy male (33 years old, 74 Kg, and height 177 cm) with a free walking speed of 1.4 m/sec was used as input for the inverse kinematic analysis. As shown in Fig. 6, the thigh segment was tracked using a total of five IREDs, three of which were placed along the lateral thigh, spaced at approximately 15 cm intervals with the middle IRED on a 5.5 cm extension. In addition an aluminum clamping device (185 g) was positioned over the condyles with a 15 cm rod extending laterally with one IRED at the end and another 10 cm proximal. The shank segment was tracked using three IREDs paced along the tibia separated by approximately 15 cm with the middle IRED mounted on a 7 cm extension. The IREDs were tracked using an Optotrak motion analysis system (model 3020, Northern Digital, Waterloo, On-

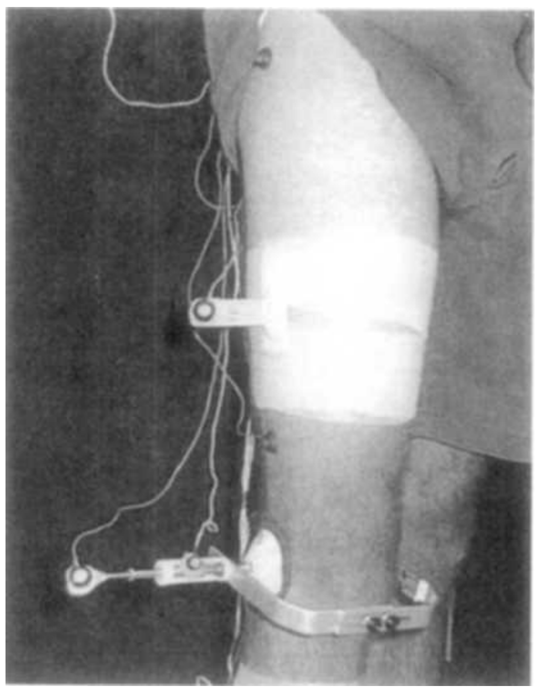

Fig. 6 Anatomical redundant marker system for the thigh segment (five-marker system)

tario) at 60 Hz. The subject walked along a 30 m walkway that contained a 3 m by 2 m data collection volume with an estimated accuracy of greater than 1 mm in all directions. Marker data were filtered at 6 Hz using a 4^{th} order Butterworth filter.

3. Results

The relative motions between the femur and tibia segments using Grood-Suntay's coordinate in terms of flexion/extension, adduction/abduction and external/internal rotations using the five skin marker system are shown in Fig. 7. The plots in the left column show the individual curves for each marker combination, while those in the right column show the mean and standard deviation as determined by the JACS method.

From the individual curves for each marker combination, maximum differences for both flexion/extension angle and adduction/abduction rotation occurred at 42% of the gait cycle, with the difference in flexion/extension being approximately 10°, and adduction/abduction rotation being about 5°. The difference between the maximum and minimum external/internal rotation is about 18°, which occurs during the swing phase, at 98% of the gait cycle. Interestingly the third

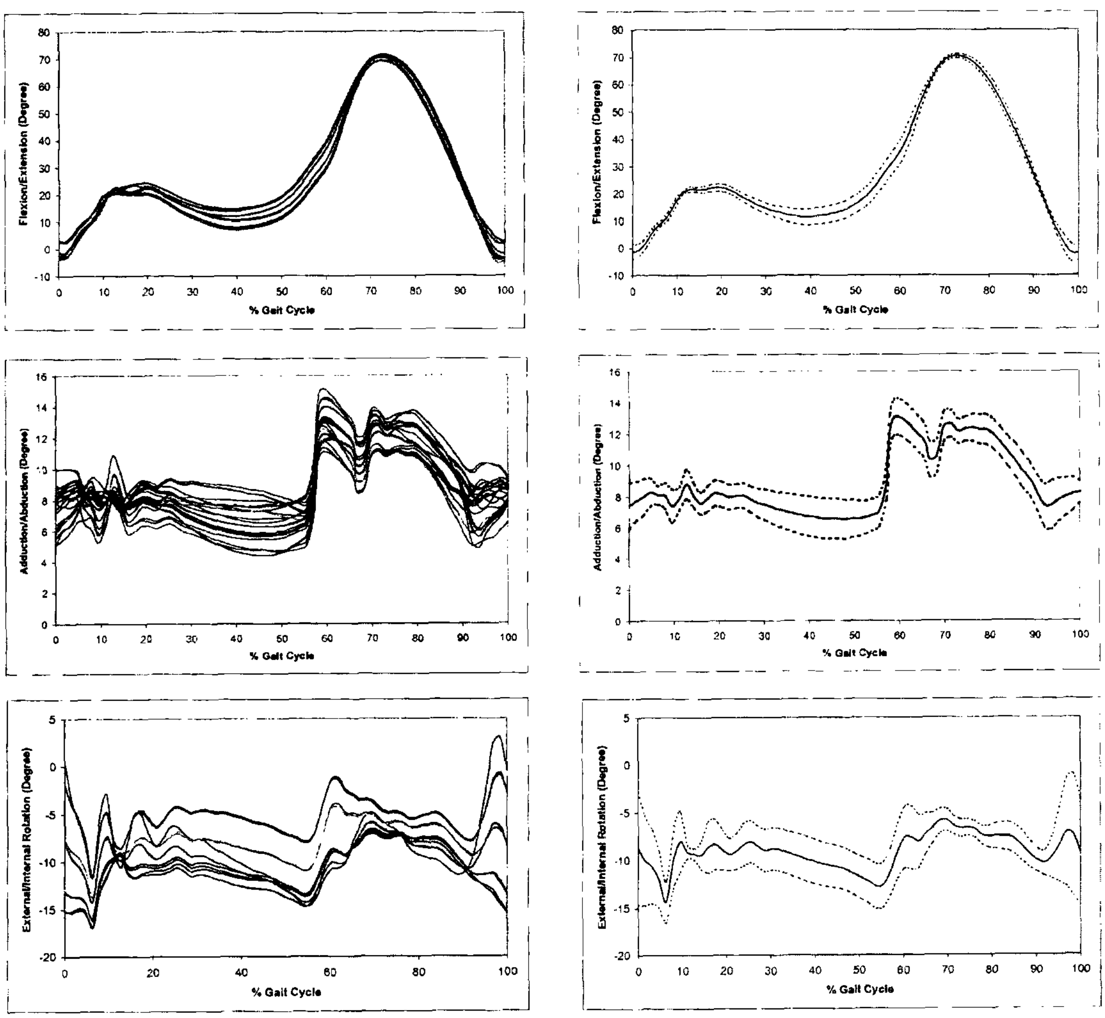

Fig. 7 Rotation angles for permuted marker combinations (left), and mean and standard deviations (right)

recovered angle, external/internal rotation, has a relatively high value of standard deviation compared to flexion/extension and adduction/abduction rotation angles through the entire gait cycle. This implies the least confidence in the value of the recovered external/internal rotation angle, as shown by other researchers (Crawford et al., 1996; Panjabi et al., 1993; Reinschmidt et al., 1997a). Additionally, the relatively large differences between knee joint rotation angles recovered through the use of different marker combinations lends justification to the JACS technique, which averages the differences, as opposed to the use of a single marker combination.

The separation and penetration distance of the contact point at medial condyle and tibial articulating surface during one gait cycle was ranged about 15 mm for Spoor & Veldpaus method, 12 mm for ACRS method and 9 mm for the proposed JACS technique as shown in Fig. 8. The separation and penetration distance at the lateral side was ranged about 6 mm, 5 mm, 5 mm for Spoor & Veldpaus, ACRS and JACS method, respectively. The absolute averaged value ($\pm S.D.$) of the separation and penetration during one gait cycle at the medical side is 2.9 ($\pm$1.7) mm, 3.2 ($\pm$21) mm and 3.6 ($\pm$2.5) mm for JACS, ACRS and Spoor & Veldpaus method, respectively, while lateral side ranged 1.3 ($\pm$0.9) mm for JACS, 1.5 ($\pm$0.9) for ACRS and 1.6 ($\pm$1.0) mm for Spoor & Veldpaus method, respectively. In addition, the maximum absolute value of the separation/penetration distance during one gait cycle is about 15 mm for Spoor & Veldpaus method, 12 mm for ACRS method and 9 mm for the proposed JACS method, which are shown up at the medial side.

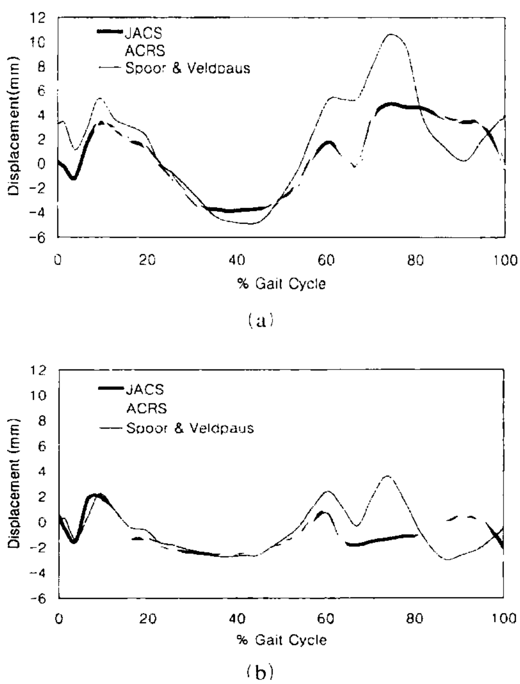

Fig. 8 Comparison of JACS, ACRS and Spoor and Veldpaus method ; (A) Displacement between medial condyle and tibia side contact point, (B) Displacement between lateral condyle and tibia side contact point

4. Discussion

In order to achieve better position kinematic data from human motion analysis, both experimental methods (Kadaba et al., 1990; Reinschmidt et al., 1997b) and numerical methods (Cheze et al., 1995; Lu and O'Connor, 1999; Spoor and Veldpaus, 1980) have been studied previously. Among the experimental methods, averaging of several gait trials for a subject with respect to one gait cycle is frequently employed (Kadaba et al., 1990; Reinschmidt et al., 1997). Often, a single reference frame is determined from the three-markers and used to represent the orientation of the body segment. This is different than the JACS method, which averages the orientation of all marker combinations from a single trial. The JACS method is a statistical-based technique using one gait trial for a subject to reduce experimental error, mainly skin movement of the thigh segment, during gait without any additional testing time or cost. The method provides quantitatively better results compared to the well-defined existed methods such as ACRS and Spoor & Veldpaus since the method averages the body segment orientation from the experimental data.

The JACS method is simple to understand and convenient to use, and can reduce errors, as shown in the results. The method can be applied to determine body segment orientation using a three-marker system as well as redundant marker systems. The JACS method can be implemented with current gait analysis software, without intervention by users.

Finite statistics show that predicted values for body segment orientation will tend toward the true values as the number of averaged values increases. This assumes that errors in the experimental data are randomly distributed, and follow a normal distribution (Figliola and Beasley, 1995). The largest experimental error component in human motion analysis is skin movement, which has both systematic and random parts. Statistical data reduction techniques, like the JACS method, address only the reduction of random errors. However, there are no limitations on combining the JACS method with methods that address the reconstruction of marker positions due to systematic errors. This would further improve estimates of body segment position and orientation during human motion.

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