International Journal of Industrial Ergonomics 39 (2009) 152–158

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Soft tissue artifact compensation using displacement dependency between anatomical landmarks and skin markers – a preliminary study

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ARTICLE INFO

Article history:
Received 10 September 2007
Received in revised form 30 April 2008
Accepted 8 May 2008
Available online 1 August 2008

Keywords:
Motion analysis
Soft tissue artifact
Anatomical landmark calibration
Skin marker displacement

ABSTRACT

Soft tissue artifact is known to be one of the principal sources of errors using human motion analysis by means of stereophotogrammetry. As one of the ways to reduce such errors, Lucchetti, L., Cappozo, A., Cappello, A., Croce, U.D. [1998. Skin movement artefact assessment and compensation in the estimation of knee-joint kinematics. Journal of Biomechanics 31, 977–984] proposed the so-called dynamic calibration in which anatomical landmark positions are calibrated in an ad hoc motion after which they are compensated with joint angles in a motor task. However, the method was proven partially inefficient during the repetitive calculation of joint angles for anatomical landmark compensation. The present study herein attempted to offset the anatomical landmark position by using a skin marker displacement as an alternative to the compensation method with joint angles. The feasibility of the proposed method was tested by analyzing the knee motions of a patient wearing an external fixator on the shank. Its performance was later compared with the compensation method with joint angles. In the test, the proposed method was identified as effective in reducing soft tissue artifact errors by 40–80%. The errors of some of kinematic variables were significantly reduced by 25–60% compared to the compensation method with joint angles.

Relevance to industry: Motion analysis with stereophotogrammetry is utilized for various purposes, including clinical diagnosis, product design, and workload assessment. However, it has been known to accommodate significant errors due to the deformation of soft tissues such as those in the skin and muscles. Methods known to efficiently reduce errors due to the soft tissues are required to improve the utilization of motion analysis. The proposed method simplifies the procedure in reducing the error, and it can be implemented more easily during routine lower extremity motion analysis. But an application of this method during measurements of motions at workplaces would require a validation of the method based on scientific standards.

1. Introduction

Skin marker-based stereophotogrammetry is most frequently used to analyze human motions because of its advantages in safety and usability. This technique puts reflective or light-emitting markers on the skin and obtains their three dimensional positions using two or more cameras. Compared with radiographic and fluoroscopic techniques, stereophotogrammetry does not expose subjects to radiation (Andriacchi et al., 1998) and takes less time and effort in measuring activities (Leardini et al., 2005).

In contrast, motion analysis based on stereophotogrammetry has been known to produce a fairly large number of errors due to the deformation of soft tissues such as those in the skin and muscles, often referred to as STA. STA causes the displacement of skin markers relative to the underlying bone and thus results to errors while analyzing skeletal movement. Skin marker displacement was found to range from 10 to 40 mm in the lower extremities (Cappozzo et al., 1996; Fuller et al., 1997), while motion analysis error due to STA was reported to range from 10 to 20° and especially significant in the aspects of ab/adduction and internal/external rotation (Cappozzo et al., 1996; Holden et al., 1997; Reinschmidt et al., 1997).

To reduce the effect of STA, some algorithms were proposed to treat the STA as independent noise irrespective to motor tasks. Soderkvist and Wedin (1993) proposed an optimization method to calculate a segmental pose, which reduces the deformation of cluster of skin markers caused by STA using the Singular Value Decomposition algorithm. Challis (1995) and Ball and Peirrynowski (1998) endeavored to model the skin marker cluster deformation using geometric transformations, such as scaling and shearing. Alexander and Andriacchi (2001) attempted to model the trajectory

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doi:10.1016/j.ergon.2008.05.005

Nomenclature

STA	soft tissue artifact
AL	anatomical landmark
TCF	technical coordinate frame
ACF	anatomical coordinate frame
LC	lateral tibial condyles
MC	medial tibial condyles
LM	lateral malleolus
MM	medial malleolus

of skin marker displacements relative to the underlying bone with Gaussian function.

Some methods assumed that there is systematic pattern in STA in relation to motor tasks and consequently attempted to produce a model for it. They assessed motor task-related patterns of STA by obtaining the positions of ALs together with skin markers at multiple postures or in an ad hoc motion. Cappello et al. (1997, 2005) proposed the double AL calibration in which AL positions are measured by a pointer at two static postures representing a motor task. Lucchetti et al. (1998) recommended the so-called dynamic AL calibration to identify AL positions in an ad hoc motion. Instead of measuring skin marker displacements by STA relative to the underlying bone, these studies innovatively assessed the relative movement of ALs in the reference coordinate frame as defined by the cluster of skin markers, which is usually referred to as TCF. Then they modeled the displacement of ALs with motion time or joint angles to compensate AL positions relative to TCF in a motor task.

The method of Lucchetti et al. (1998) obtained a certain degree of inefficiency in the repetitive calculations of joint angles to compensate AL displacements. In an ad hoc motion and a target motor task, the method calculates joint angles to model the AL displacement and to estimate AL displacements, respectively. In addition, joint angles are reconstructed from the AL positions compensated with estimated AL displacement. Considering the size of position data of skin markers and number of steps needed in joint angle calculation, the repetition of joint angle calculation makes the compensation procedure complex.

The present study proposed an alternative to the research of Lucchetti et al. (1998) on AL position compensation with joint angles. It assumed that the AL displacement is associated with the displacement of some skin markers in an identical TCF, and consequently attempted to model the dependency between them. Given that the calculation of the skin marker displacement is considered simple, AL position compensation with skin marker displacement will take much less time and effort than with joint angles. The feasibility of the proposed method was tested by analyzing the knee motions of a patient wearing an external fixator on the shank, and its performance was compared with the AL position compensation method with joint angles.

2. Methods

2.1. AL compensation with skin marker displacement

The method of Lucchetti et al. (1998) calibrates AL positions of a segment wherein the skin marker cluster of a neighbor segment is unaffected by STA during ad hoc motion. STA affects the segment near the rotated joint but not those away from it because the STA of a segment mostly originates from the rotation of the adjacent joints (Cappozzo et al., 1996) during a joint rotation wherein an adjacent joint is fixed. Based on this idea, AL positions of the segment near the rotated joint are identified with their local coordinate in reference to the TCF of the STA-free segment during ad hoc motion. For example, if the local coordinates of femoral head, lateral, and medial epicondyle on the thigh are fixed in a TCF on the shank in a standing static posture, using them in global positions allows for their identification during hip-joint swing motion with knee fixed (see Fig. 1).

Using the calibrated AL positions, the relative movement of ALs in the TCF of a segment, also referred to as AL displacement, can be obtained during ad hoc motion. Due to STA, the pose of the TCF as defined by skin markers becomes deformed relative to the underlying bone. Therefore, the relative positions of ALs change during motion in the reference of TCF even if they are rigid to the underlying bone. As shown in Fig. 2a, if the local coordinate (r_a) of an AL is fixed in the TCF as defined by S_1–S_3 in a static posture, when compared during the ad hoc motion, the AL displacement (Δr_a) becomes the difference between the calibrated AL positions and those reconstructed by r_a and the deformed TCF (Fig. 2b).

Likewise, during the same motion, the displacement of some skin markers other than those used to define a TCF can be obtained in the reference of the TCF. While STA has a systematic pattern with regard to a motor task, its effect on each marker differs depending on their positions. As shown in Fig. 2, if the local coordinate (r_s) of an additional skin marker S_4 is fixed in the TCF, the displacement (Δr_s) of S_4 during the motion becomes the difference between its measured positions and those reconstructed by r_s and the deformed TCF.

The proposed method models a relationship between the displacements of AL and the skin marker in a linear form. The AL displacement relative to a TCF is known to be dependent on joint angle. In addition, the skin marker displacement relative to a TCF will be dependent on joint angle because it is caused by a systematic movement of STA that is related to a joint angle. The proposed method aims to find a dependency between AL and the skin marker displacements. Using a correlation analysis, the method identifies an axial component of a skin marker displacement that is highly correlated with each axial component of an AL displacement. Then, the AL displacement model is developed using a highly correlated component of the skin marker displacement as represented in a linear regression form. The AL displacement models are confined to a linear form because such is simple to develop and it makes the models consistent between model developers.

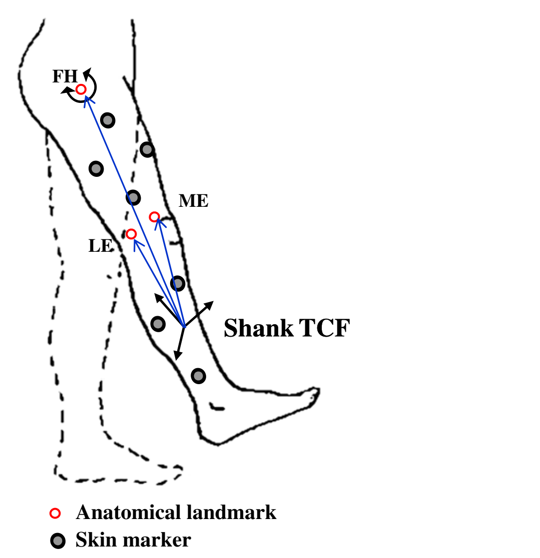

Fig. 1. AL identification in hip-joint swing motion with knee extended.

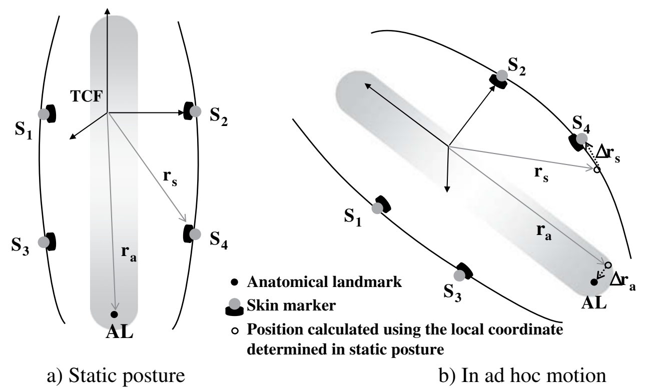

Fig. 2. Displacements of AL and a skin marker (S_4) to a TCF defined by S_1–S_3.

During a motor task, the AL positions are compensated using the developed AL displacement models. At each frame of motion, the skin marker displacement in the reference of a TCF is calculated. The AL displacement in the TCF is subsequently estimated with the developed AL displacement model. The AL position is adjusted by adding the estimated AL displacement to the AL local coordinate in the TCF, which is fixed in a static posture. Lastly, joint kinematics is analyzed using the compensated AL positions.

2.2. Experimental setup for validation

A motion measurement system using six cameras (Falcon, MotionAnalysis) was used to measure knee motions (sampling frequency 60 Hz, measurement volume $4 \times 3 \times 2$ m). The accuracy of the system was assessed for error and variation in the measured distance between the two markers mounted on a rod according as described by Ehara et al. (1997). The mean and maximum errors of this distance were 0.63 mm and $\pm$3.30 mm, respectively. The SD of the measured distance was 0.82 mm.

One female patient wearing an external bony fixator on the right shank participated in the experiment. The participants signed an informed consent. The height, weight, and age of the patient were 1.63 m, 56 kg, and 42 years, respectively. The motion measurement was conducted the day before the external fixator was removed.

Reflective markers (20 mm diameter spherical balls) were placed on the shank of the patient. Five (M1–M5) and three markers (E1–E3) were located on the shank and the external fixator, respectively (see Fig. 3). To test the feasibility of the proposed method in various marker arrangements, two marker clusters (M1, M2, M5 and M1, M2, M3) were used in motion analysis. The markers on the fixator, as a gold standard, were used to analyze the skeletal movement. In addition, AL positions rigid to the tibia/fibula are obtained using the fixator markers which were identified during knee motions.

ACF of the shank was defined according to Wu et al. (2002) using LC, MC, LM and MM. The origin of the ACF is coincident with the mid-point of LM and MM; the z-axis on the line connecting MM to LM; the x-axis frontally orthogonal to the plane with LM, MM and the mid-point of LC and MC; and the y-axis on the cross vector of the z- and x-axis.

The patient performed three motor tasks: in sitting static posture and two sets of repeated knee motions. Sitting static posture for anatomical calibration was maintained for about two minutes, after which two set of repeated knee motions of the right leg while keeping a sitting posture and the left foot on the ground was performed. The first set of knee motions was used for modeling AL displacement, and the second for validating the proposed method.

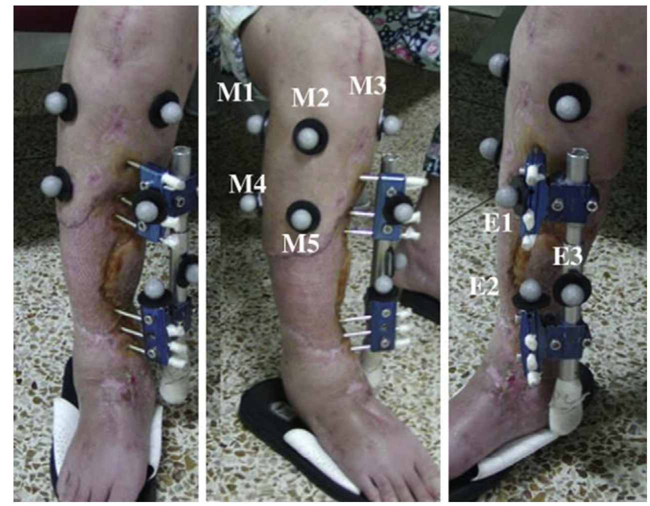

Fig. 3. Marker placement.

2.3. Anatomical calibration

The AL calibration was performed in a sitting static posture using a pointer on which two markers were mounted with a known distance. The position of LC, MC, LM, and MM was measured by pointing the tip of the pointer onto the corresponding palpable ALs. Meanwhile, the markers on the shank and the fixator were also measured.

The AL position relative to the two skin marker clusters (M1, M2, M5 and M1, M2, M3) on the shank and one marker cluster (E1, E2, and E3) on the fixator was fixed through geometric calculation. Two TCFs (TCF[1] by M1, M2, M5 and TCF[2] by M1, M2, M3) were defined, and the local coordinate of each AL was fixed in each TCF. Likewise, the coordinate frame of the fixator was defined by markers E1, E2 and E3. The local coordinate of each AL was also fixed in the frame.

2.4. Pose calculation of coordinate frames

During motion, the pose of the shank TCFs was calculated using the Singular Value Decomposition algorithm of Soderkvist and Wedin (1993). The position vector and orientation matrix of each TCF was obtained from the transformation matrix, which was estimated

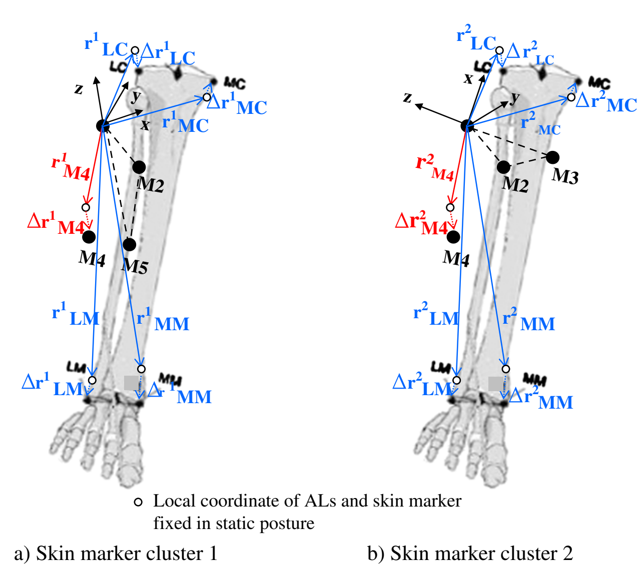

Fig. 4. AL and skin marker displacements.

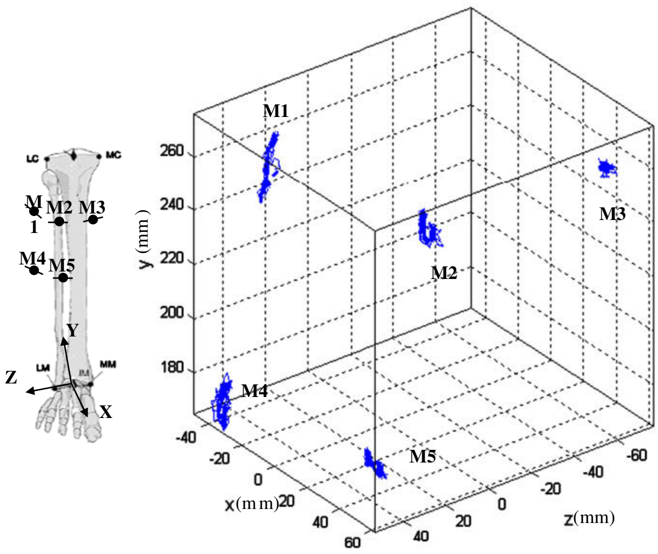

Fig. 5. Trajectory of skin marker displacements relative to the tibia/fibula.

by the algorithm between the local coordinate of the three relevant skin markers in the TCF and their global positions. The pose of fixator coordinate frame was also calculated in the same way in relation to the transformation matrix between the local coordinate of the fixator markers in the frame and their global positions.

2.5. AL and skin marker displacement

The displacements of the ALs and the skin marker M4 were obtained in the reference of the two shank TCFs using the recording in the first knee motions. The positions of ALs (LC, MC, LM, and MM) were reconstructed using the fixator pose and the relevant AL local coordinates. Then, as shown in Fig. 4, the AL displacements were calculated as the difference between the local coordinate of the reconstructed ALs and those fixed in the sitting static posture for the two TCF of the shank, respectively. Likewise, the displacement of skin marker M4 was calculated by subtracting from the measured ones the local coordinate in each TCF fixed in the static posture.

The relationship between the displacements of the ALs and skin marker M4 was modeled in a linear form. Each axial component of an AL displacement was plotted with the three axial components of M4 displacement. A component of M4, which had the highest correlation coefficient with it, was identified. The AL displacement model was developed using a simple regression form. Moreover, to compare the proposed method and the AL compensation method with joint angle as mentioned by Lucchetti et al. (1998), the AL displacement was also modeled with shank rotation in sagittal plane.

The AL positions during the second knee motion were compensated with the developed AL displacement models. At each frame of the motion, AL displacements were estimated using the developed models. The displacement of M4 and the local coordinate of the ALs in each TCF fixed in the static posture were adjusted in relation to the relevant AL displacements.

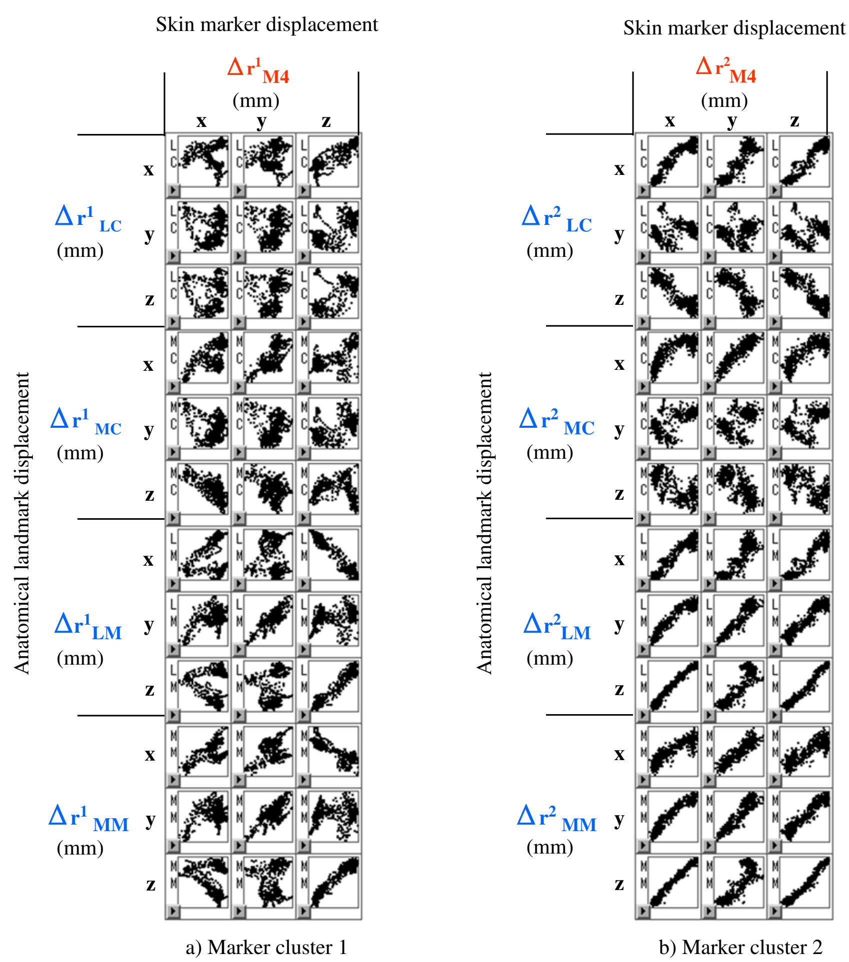

Fig. 6. Scatter plot of AL and skin marker displacements.

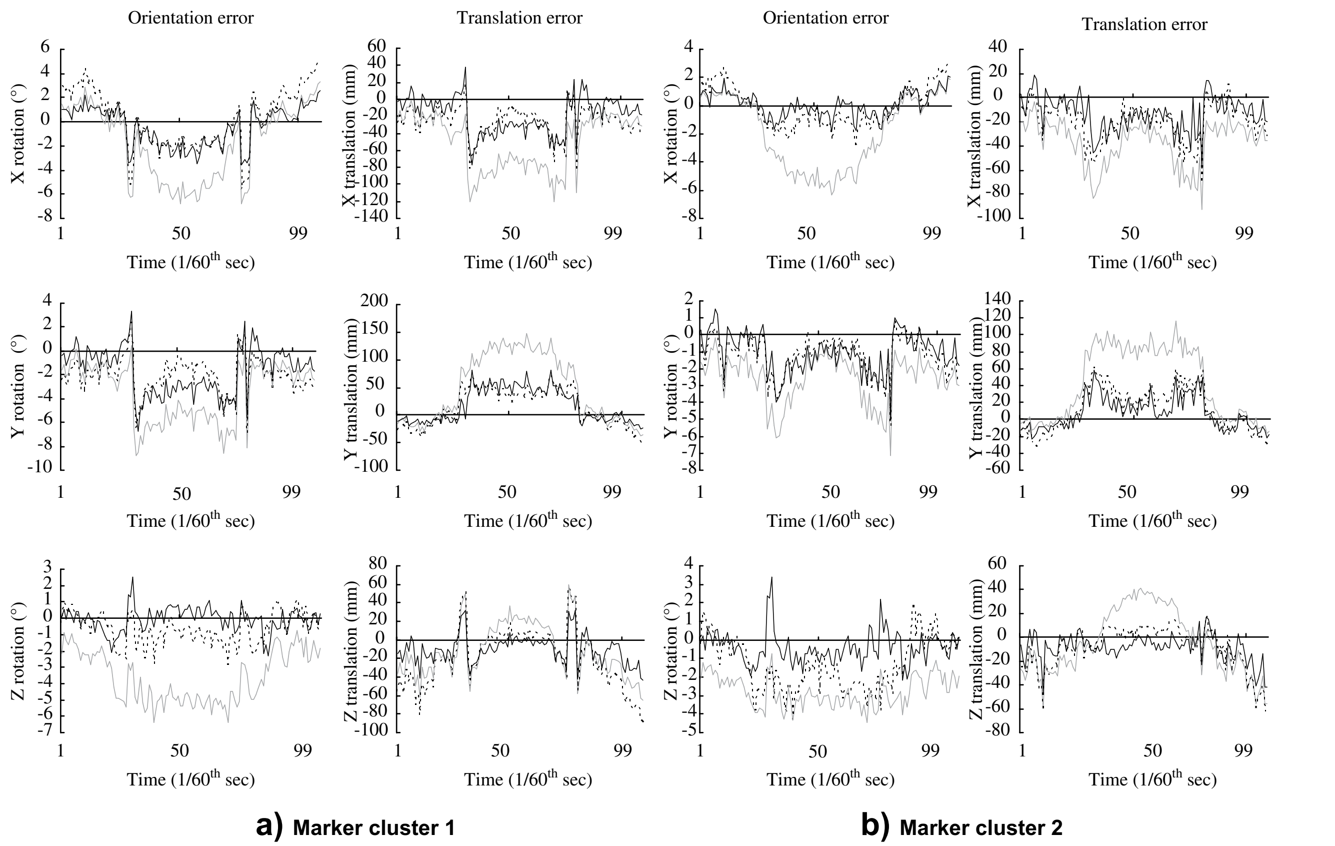

Fig. 7. Kinematic errors of the three methods in motion analysis of the patient (solid black: with compensation using skin marker displacement, dashed black: with compensation using rotation angle, solid gray: without compensation).

2.6. Motion analysis methods

Knee motion was analyzed using three methods: the proposed method, the method of Lucchetti et al. (1998), and the method of Soderkvist and Wedin (1993). The proposed method and the method of Lucchetti et al. were composed of AL compensation methods with skin marker displacements and with joint angles, respectively. The method of Soderkvist and Wedin (1993) was used to analyze the knee motion without AL compensation.

2.7. Statistical analysis

One-way analysis of variance (ANOVA) was conducted to test if the motion analysis errors are affected by the three analysis methods. A Student–Newman–Keuls (SNK) test was used to compare the errors statistically across methods. For each kinematic variables, time series errors were obtained. Moreover, one-way ANOVA was performed with the analysis methods as independent variable. For the error on which the effect of analysis methods is significant, SNK test was conducted to analyze if the errors of analysis methods are statistically different from each other.

3. Results

3.1. Skin marker displacement relative to the underlying bone

At the beginning of the process, the displacement of the five skin markers was analyzed during the first knee motions. This was obtained by calculating the local coordinates of the markers for each time frame of the motion with reference to the shank ACF. The pose of shank ACF was reconstructed using the ALs identified with the fixator coordinate frame and their local coordinates. The skin marker displacements of M1–M5 during the motion are shown in Fig. 5. The magnitude of the displacements was 4.0–18.3 mm depending on the locations of the markers. This was similar to the results of Cappozzo et al. (1996) and Lafortune and Lake (1991).

3.2. AL displacement model

There was a dependency between the displacements of the ALs and the skin marker M4 in the corresponding TCFs in the first set of knee motion. The plots between the AL displacements (Δr^{G1}_{LC}, Δr^{1}_{MG} Δr^{1}_{LM}, Δr^{1}_{MM} in TCF^1, and Δr^{2}_{LC}, Δr^{2}_{MC}, Δr^{2}_{LM}, Δr^{2}_{MM} in TCF^2) and M4 displacements (Δr^{1}_{M4} in TCF^1 and Δr^{2}_{M4} in TCF^2) are shown in Fig. 6. The study identified one axial component that was highly correlated with each component of AL displacements. Most AL displacements had a high dependency with at least one of the three axial components of the displacements of M4. However, the *y* and *z* components of Δr^{1}_{LC} and Δr^{1}_{MC} had a weak dependency with the displacement of M4. This is similar with the *y* component of Δr^{2}_{LC} and *y* and *z* components of Δr^{2}_{MC}.

A simple model for each axial component of AL displacements was made from those having a linear regression form in relation to the axial component of the skin marker displacement having the highest correlation coefficient. Of a total of 24 models for AL displacements, 18 models had R^2 values higher than 0.5.

3.3. Motion analysis error

The rotational and translational errors relative to the gold standard during the second knee motions are shown in Fig. 7 as obtained with (using skin marker displacement and joint angles)

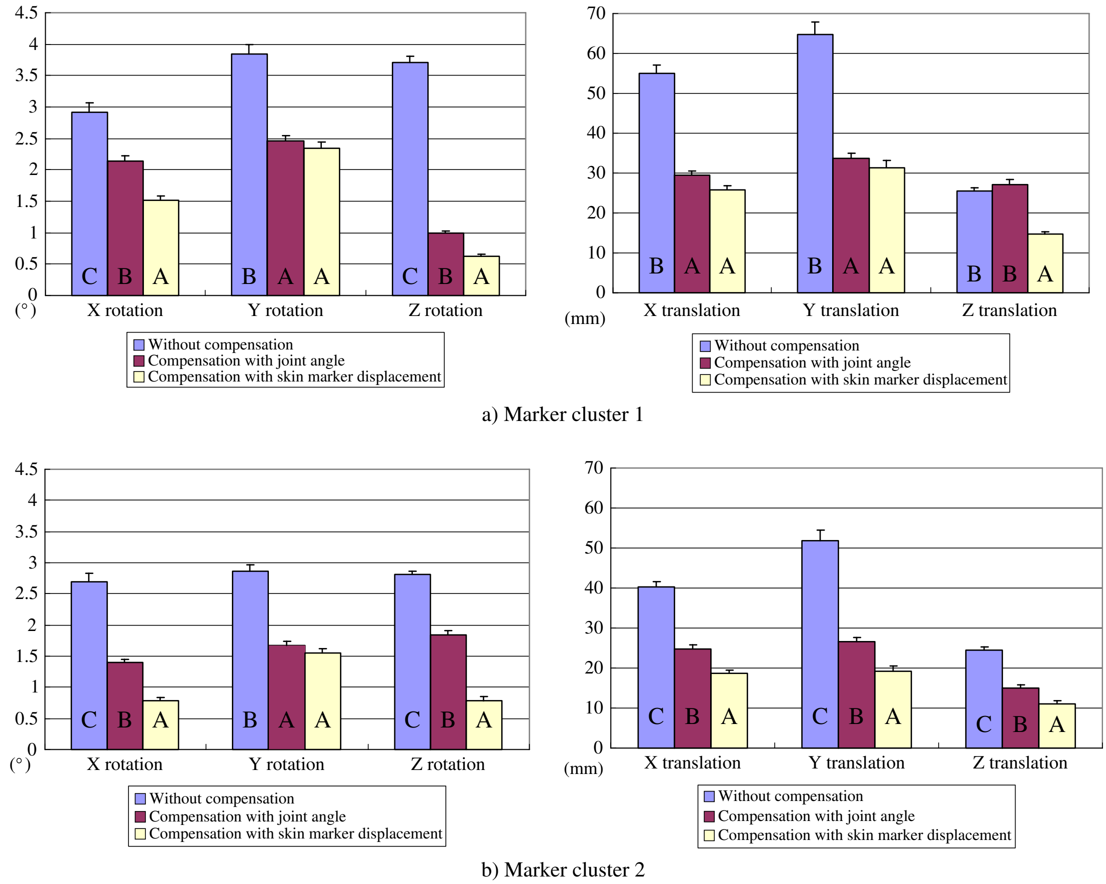

Fig. 8. Student–Newman–Keuls (SNK) test of motion analysis errors. The statistical groups of the errors were presented with the alphabetic letters A, B and C.

and without AL compensation. Regardless of marker clusters used in motion analysis, AL compensation methods had smaller errors than without compensation as evident in all the kinematic variables. One-way ANOVA showed that the errors of all the kinematic variables were significantly affected by analysis methods at $\alpha = 0.05$. The results of the Student–Newman–Keuls (SNK) test for the errors of the three methods ($\alpha = 0.05$) are shown in Fig. 8. The AL compensation with skin marker displacement had significantly smaller errors (39–83%) than without compensation in all the kinematic variables for the two marker clusters. Moreover, it had significantly smaller errors (25–58%) than the compensation with joint angles in *X*-, *Z*-rotation, and most translational motions, except along *X*- and *Y*-axis for marker cluster 1 wherein no significant difference was found.

4. Discussion and conclusions

Both AL compensations (with skin marker displacement and joint angles) were effective in reducing the STA errors. In the validation experiment, all the rotational and translational errors were significantly reduced by 40–80% by the AL compensation with skin marker displacement relative to without compensation. In addition, most of the rotational and translational errors were significantly reduced by AL compensation with joint angles by 30–70%.

In terms of motion analysis procedure, the two AL compensation methods are considerably complex. Both require the four additional steps: (1) calibrating AL positions in an ad hoc motion, (2) calculating the AL displacement, (3) modeling AL displacements, and (4) compensating AL position with the developed models during a motor task. The AL compensation methods should develop AL displacement models for each person through these steps. However, the benefits of the AL compensation methods outweigh the costs as shown in the validation results of the present study.

Of the two AL compensation methods, the one using skin marker displacement offered slightly more effectiveness in analyzing knee motions. In the validation test, all of the kinematic errors were reduced by the AL compensation with skin marker displacement than with the joint angles. Some of the differences in errors between the two methods were statistically significant at 25–60% reductions.

The AL compensation with skin marker displacement develops the AL displacement model and estimates AL displacement more efficiently than with joint angles. The former develops the AL displacement model and estimates AL displacement from the AL and skin marker data of the corresponding segment. In contrast, the latter requires the skin marker data of a neighboring segment, apart from the AL and skin marker data of the segment, to calculate joint angles. Also, it requires a series of steps to calculate joint angles repeatedly to compensate AL positions.

Between the two marker clusters used in the feasibility test, marker cluster 2 was noted better in reducing the motion analysis error compared to the cluster 1 in the AL compensation method with skin marker displacement. Markers of cluster 1 consisted of M1, M2 and M5, and cluster 2 with M1, M2 and M3. The mean displacement of M5 to the underlying bone (4.0 mm) was larger than M3 displacement (3.0 mm), thus the TCF of marker cluster 2 was noted of being more stable during motion than that of cluster 1. In addition, the R^2 of AL displacement models using marker cluster 2 was noted slightly higher than using cluster 1. As such, the proposed method may reduce the motion analysis errors more effectively with a relatively stable TCF.

The validation experiment of this study has several limitations and thus further validation study is required. The skin marker movements due to STA differ across individuals. In this study, only a female subject was sought for the validation experiment. The skin marker movements may differ from those of 'normal' persons because the female subject had an external bony fixator. In addition, motion analysis was conducted only for simple knee motions but not for working activities such as walking. Further validation study will be planned out to resolve these problems. More persons may be asked to participate and various working activities will be analyzed with the proposed method.

The proposed method reduces the effect of STA related to the movement of the underlying bone and is applied only to relative slow movements. During the fast movements, such as walking quickly and running, a skin marker also becomes affected by its own acceleration and vibration, as well as the underlying bone movements. It is difficult to apply the proposed method to the fast movements because the proposed method compensates only the skin marker displacement related to the underlying bone movement.

In conclusion, this study proposes an alternative to the AL displacement modeling with joint angles earlier offered by Lucchetti et al. (1998). This method models the AL displacement with skin marker displacement instead of joint angles, and compensates AL positions more efficiently by removing the repetitive joint angle calculation. As presented in the results of the validation test, the proposed method was effective in STA error reduction similar to the previous method. However, it is necessary to validate the proposed method across various people, especially those who are able-bodied.

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