http://dx.doi.org/10.11627/jkise.2012.35.4.24

pISSN 2005-0461
eISSN 2287-7975

Application of Compensation Method of Motion Analysis Error Using Displacement Dependency between Anatomical Landmarks and Skin Markers Due to Soft Tissue Artifact

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연조직 변형에 의한 해부학적 지표와 피부마커의 변위 상관성을 이용한 동작분석 오차 보정 방법의 적용

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Of many approaches to reduce motion analysis errors, the compensation method of anatomical landmarks estimates the position of anatomical landmarks during motion. The method models the position of anatomical landmarks with joint angle or skin marker displacement using the data of the so-called dynamic calibration in which anatomical landmark positions are calibrated in ad hoc motions. Then the anatomical landmark positions are calibrated in target motions using the model. This study applies the compensation methods with joint angle and skin marker displacement to three lower extremity motions (walking, sit-to-stand/stand-to-sit, and step up/down) in ten healthy males and compares their performance. To compare the performance of the methods, two sets of kinematic variables were calculated using different two marker clusters, and the difference was obtained. Results showed that the compensation method with skin marker displacement had less differences by 30~60% compared to without compensation. And, it had significantly less difference in some kinematic variables (7 of 18) by 25~40% compared to the compensation method with joint angle. This study supports that compensation with skin marker displacement reduced the motion analysis STA errors more reliably than with joint angle in lower extremity motion analysis.

Keywords : Motion Analysis, Soft Tissue Artifact, Anatomical Landmark Calibration and Compensation, Skin Marker Displacement

1. Introduction

Skin marker-based motion analysis is the most commonly used technique to analyze motions, despite significant errors due to the deformation of soft tissues such as skin and muscle. The displacement of skin markers relative to the underlying bones is called soft tissue artifact (STA), and it is responsible for errors in motion analysis. Skin marker displacement can be as much as 40 mm in the lower extremities [7, 9]. Error in computed angle due to STA ranges from 10 to 20°, and is especially significant in abduction/adduction and internal/external rotation motions [7, 10, 13].

Methods proposed to reduce STA errors are based on ei-

Received 21 June 2012; Finally Revised 9 August 2012;
Accepted 7 October 2012

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ther one of two principles : 1) treating the STA as an independent noise irrespective of motor tasks and 2) modeling a systematic pattern of STA in relation to motor tasks. Representatives of the first category are the studies of Challis et al. [3], Ball and Peirrynowski [2] and Alexander and Andriacchi [1]. Challis et al. [3] and Ball and Peirrynowski [2] made models of skin marker cluster deformation using geometric transformations, such as scaling and shearing. Alexander and Andriacchi [1] attempted to model the trajectory of skin marker displacements relative to the underlying bones using the Gaussian function.

The second category includes methods that assessed task-related patterns of STA by obtaining the positions of anatomical landmark (AL)—which indicates the skeletal pose—and skin markers at multiple postures or in an ad hoc motion. Cappello et al. [4] and Cappello et al. [5] proposed the double AL calibration, in which AL positions are measured by a pointer at two static postures in a motor task. Lucchetti et al. [11] proposed the so-called dynamic AL calibration to identify AL positions in an ad hoc motion. Instead of measuring STA skin marker displacements relative to the underlying bones, they innovatively assessed the relative movement of ALs in reference to the coordinate frame defined by the cluster of skin markers, referred to as technical coordinate frame (TCF) defined by skin markers. They modeled the displacement of ALs against motion time or joint angle to correct AL positions relative to TCF when performing a motor task.

As an alternative to AL position compensation with joint angle, Ryu et al. [14] proposed AL position compensation with skin markers. They assumed that AL displacement is associated with skin marker displacements in the same TCF, and attempted to model the relationship between them. They showed that the method was more effective than the AL position compensation with joint angle, although they tested only by analyzing knee motions of a patient wearing an external fixator on the shank.

The present study applied the two AL position compensation methods in real lower extremity movements of healthy people. This involved motion analysis of the hip, knee and ankle joints in three lower extremity motions, walking, sit-to-stand/stand-to-sit, and step up/down, in 10 healthy males. The performance of the compensation method with skin markers was compared to the method with joint angle.

2. Methods

2.1 Experimental Setup

A motion measurement system with six cameras (Falcon, MotionAnalysis) was used to measure lower extremity motions (sampling frequency 60 Hz, measurement volume 4×3×2m). The accuracy of the system was assessed by comparing the measured distance between two marker positions to the known distance, such that the variation of the distance indicates error, as described by Ehara et al. [8]. Mean error of the marker distance was 0.63 mm, maximum error was ±3.30 mm, and SD of the distance was 0.82 mm.

Ten healthy young males with no previous history of musculoskeletal or neurological disorders related to the lower extremities participated in the experiment. The mean height, weight, and age of the participants were 1.75 m (SD = 0.03), 69.3 kg (SD = 5.8), and 26.2 years (SD = 3.0), respectively. All the participants signed informed consent forms.

Anatomical coordinate frame (ACF) defined by ALs of the pelvis, thigh, shank, and foot of the participants were defined according to Capozzo et al. [6]. Left/right anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS) defined the ACF of the pelvis, whereas femoral head (FH), and lateral and medial epicondyles (LE and ME) were used for the thigh. Detailed definitions of the ACFs for all lower limb segments are presented in <Table 1>.

Twenty reflective markers (20 mm diameter) were placed on the right lower limb segments of the participants (<Figure 1>). Four markers (P1-P4) were located on the palpable point of ALs of the pelvis, and four markers (F1-F4) were placed randomly on the foot. Two sets of six markers (T1-T6 and S1-S6) were placed on the thigh and the shank, respectively. These were grouped into two marker clusters, T1-T4 and T3-T6 for the thigh, and S1-S4 and S3-S6 for the shank.

The participants performed six motor tasks: 1) standing static posture; 2) Flexion/extension (FL/EX), AB/AD, and IN/EX of hip joint; 3) hip joint swing motion with fixed knee joint; 4) sitting static posture; 5) knee joint motion with fixed ankle; and 6) walking, sit-to-stand/stand-to-sit and step up/down. Standing and sitting static postures were held for 1-2 minutes for AL calibration, and hip joint FL/EX, AB/AD, and IN/EX were performed to identify the center of the hip joint. Hip joint swing motion with fixed knee (extended) and knee joint motion with fixed ankle (dorsiflexed) were conducted as ad hoc motions for the dynamic AL calibration.

<Table 1> Definition of ACF of Lower Extremities

Segment	Definition
Pelvis	Origin : the mid-point of left and right ASIS z : connecting left ASIS to right ASIS y : orthogonal to the plane defined with left and right ASIS and the midpoint left and right PSIS x : the cross vector of Y and Z
Thigh	Origin : the midpoint of LE and ME y : connecting the origin to FH x : orthogonal to the plane defined with LE, ME, FH z: the cross vector of X and Y
Shank	Origin : the midpoint of lateral malleolus (LM) and medial malleolus (MM) y : intersection of the plane defined by LM, MM and head of fibula (HF) and the plane defined by tibial tuberosity (TT) and the midpoint of LM and MM; positive direction is proximal x : orthogonal to the plane defined by LM, MM and HF z : the cross vector of X and Y
Foot	Origin : calcaneus (CA) y : intersection of the plane defined by CA, first metatarsal head (FM) and fifth metatarsal head (VM) and the plane defined by CA and second metatarsal head (SM); positive direction is proximal x : orthogonal to the plane defined by CA, FM and VM z : the cross vector of X and Y

Walking, sit-to-stand/stand-to-sit, and step up/down were performed as target motions for analysis.

2.2 Anatomical Calibration

AL calibration was performed in both standing and sitting static postures using a pointer on which two markers with a known distance were mounted. In the standing static posture, the position of LE and ME of the thigh, and that of FM, SM, VM, and CA of the foot were identified. The position of FH was estimated as the center of marker trajectory in various hip motions, based on the method of Piazza et al. [12]. Then, the position of HF, TT, LM, and MM of the shank were identified in the sitting posture.

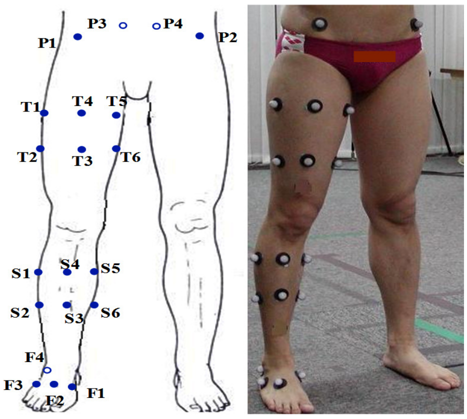
Geometric calculations were used to determine the positions of thigh and shank ALs relative to the TCFs on the corresponding body segments and on neighboring segments. The AL position relative to the TCFs on neighboring segments is measured because the neighboring segment is unaffected by STA during ad hoc motions, such as hip joint swing with knee fixed and knee joint motion with ankle fixed. Thus, this information is necessary to calibrate the AL position during motions. Two thigh TCFs (TCF^1 by T1, T2, T3 and TCF^2 by T4, T5, T6) and two shank TCFs (TCF^1 by S1, S2, S3 and TCF^2 by S4, S5, S6) were defined. The local coordinates of each AL of the thigh and shank were fixed in each TCF. The local coordinates of each thigh AL were also fixed in a shank TCF, and those of each shank AL were fixed in the TCF of the foot by markers F1-F4.

2.3 Pose Calculation of Coordinate Frames

The pose of all the TCFs and ACFs during motion was calculated using the Singular Value Decomposition algorithm of Soderkvist and Wedin [15]. The position vector and orientation matrix of each TCF were obtained from the transformation matrix, which was estimated by the algorithm between the local coordinates and global positions of the three relevant skin markers in the TCF. Likewise, the transformation matrix of each ACF was obtained from the local coordinates and estimated global positions of the relevant AL in the ACF.

2.4 AL and Skin Marker Displacement

The displacements of the ALs and skin markers on the thigh during the hip joint swing motion with fixed knee were obtained in reference to the two thigh TCFs. The positions of ALs (LE, ME, and FH) were reconstructed using a shank TCF and the relevant AL local coordinates. AL displacements were calculated as the difference between the local coordinates of the reconstructed ALs and those fixed in the standing static posture for the two thigh TCFs. Likewise, the displacement of skin markers T4 (for thigh TCF^1) and T3 (for thigh TCF^2) was calculated by subtracting the local coordinates in each thigh TCF fixed in the static posture from the measured ones during motion. In the same way, the displacements of ALs (HF, TT, LM and MM) and skin markers S4 (for shank TCF^1) and S3 (for shank TCF^2) during the knee joint motion with fixed ankle were obtained in reference to the two shank TCFs.



<Figure 1> Marker Placement on the Participants

The relationship between the displacements of ALs and skin markers was represented in a linear model using a simple regression form. Each axial component of an AL displacement was plotted with the three axial components of the relevant skin marker displacement. The skin marker component with the highest correlation coefficient with AL displacement was identified. Moreover, AL displacement with joint rotation in the sagittal plane was modeled to compare the alternative method of Ryu et al. [14] with the AL compensation method with joint angleby [11]. AL positions during the target lower extremity motions were corrected using the developed AL displacement models. At each frame of the motion, AL displacements were estimated from the models. Local coordinates of the ALs in each TCF fixed during the static posture were adjusted in relation to the relevant AL displacements.

2.5 Motion Analysis Methods

Target lower extremity motions were analyzed using three methods : the compensation method with skin markers [14], with joint angle of Lucchetti et al. [11], and Singular Value Decomposition algorithm of Soderkvist and Wedin [15]. The method of Soderkvist and Wedin [15] was used to analyze the target motions without AL compensation.

2.6 Evaluation of Motion Analysis Performance

Performance of the three methods was determined by the difference between two sets of kinematic variables estimated using two marker clusters, as described by the method of [11]. The effect of STA on skin markers varies across different locations, such that the kinematic variables estimated from two different marker clusters without STA compensation will greatly differ.

2.7 Statistical Analysis

Two-way analysis of variance (ANOVA) was conducted to determine if motion analysis differences are affected by the type of analysis method and the type of target motion. For each kinematic variable, time series differences were obtained. Then, two-way ANOVA was performed with the type of analysis method and type of motion as independent variables. Differences found to be significantly affected by analysis method or motion type were further examined using the Student-Newman-Keuls (SNK) test to determine if the differences are statistically different from one another.

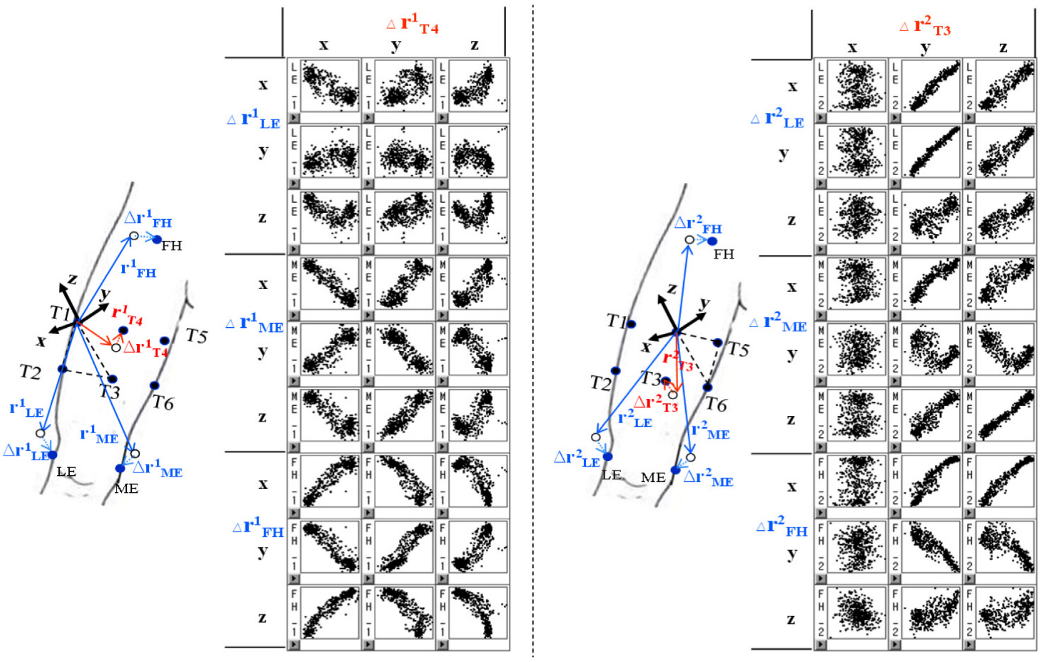
3. Results

3.1 AL Displacement Model

There was a dependency between the displacements of the ALs and the skin marker in the corresponding TCFs in the ad hoc motions. The plots between the thigh AL displacements ($\triangle\gamma^{1}_{LE}$, $\triangle\gamma^{1}_{ME}$, $\triangle\gamma^{1}_{FH}$ in TCF1, and $\triangle\gamma^{2}_{LE}$, $\triangle\gamma^{2}_{ME}$, $\triangle\gamma^{2}_{FH}$ in TCF^{2}) and the thigh skin marker displacements ($\triangle\gamma^{1}_{T4}$ in TCF^{1}, $\triangle\gamma^{2}_{T3}$ in TCF^{2}) for a participant are shown in <Figure 2>. Most AL displacements had a high dependency with at least one of the three axial components of the displacements of the skin markers. However, the y and z components of $\triangle\gamma^{1}_{LE}$ had a weak dependency with the displacement of T4, and this was similar with the y component of γ^{2}_{ME} and z component of $\triangle\gamma^{2}_{FH}$.

Likewise, most of the shank AL displacements (HF, TT, LM, and MM) had a high dependency with the shank skin marker displacements (S4 and S3). This study identified one axial component of the skin markers that was highly correlated with each component of AL displacements.

A simple regression model for each axial component of AL displacements was made with the skin marker displacement having the highest correlation coefficient with it. The AL displacement model was confined to linear form because it was simple to develop and it made the anatomical displacement models consistent between model developers. For example, of a total of 42 models for AL displacements for one participant, 32 models had R^{2} values higher than 0.5.



a) Marker cluster 1 b) Marker cluster 2

<Figure 2> Scatter Plot of AL and Skin Marker Displacement of the Thigh of a Participant

3.2 Motion Analysis Difference

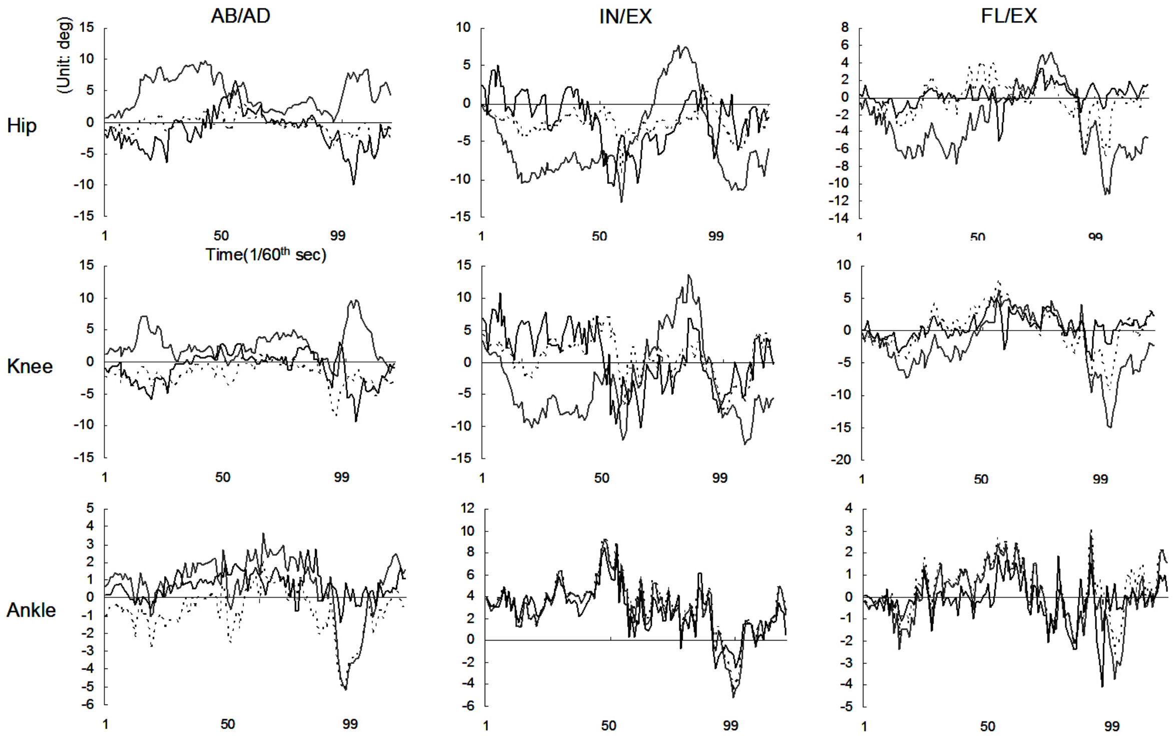
<Figure 3> presents the differences between the joint angular motions of lower extremities estimated using two marker clusters during walking and sit-to-stand/stand-to-sit. The differences between the two estimated angular motions of the hip and knee joints were apparently more reduced with AL compensation using skin marker displacement and joint angle than without AL compensation. On the other hand, the differences during ankle angular motions were similar for all three methods and did not vary with compensation. The same trends were observed in step up/down motions.

Mean difference of each pairs of estimated kinematic variables was calculated over time for the 10 participants, respectively. Mean differences of each pairs were analyzed using two-way analysis of variance (ANOVA). The effect of motion type (walking, sit-to-stand/stand-to-sit, and step up/down), analysis method (compensation with skin marker displacement and joint angle, and without compensation), and their interaction with the mean differences for 18 kinematic variables are shown in <Table 2>. For most kinematic variables, the mean differences were significantly affected by the analysis method, except for the antero-posterior motion of the hip joint (p = 0.45) and the longitudinal motion of the ankle joint (p = 0.80). They were not significantly different for varying motion types, except for IN/EX of hip (p = 0.01) and knee joints (p = 0.11). Furthermore, the interaction of the motion type and analysis method was significant only for the knee FL/EX (p = 0.02), ankle IN/EX (p = 0.03), and hip medio-lateral (p = 0.02) motions.

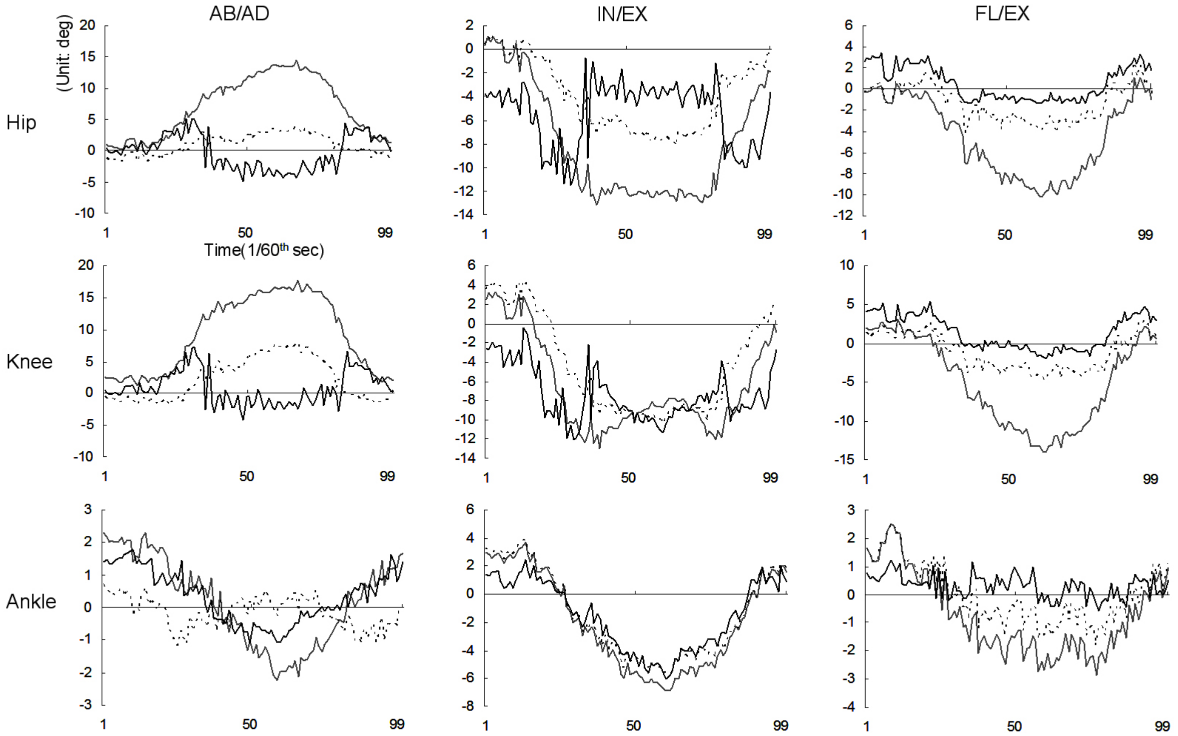
<Table 2> ANOVA Summary of Mean Difference of Kinematic Variables between Marker Clusters (p Value)

Joint	Kinematic variable	Motion type	Method	Motion type X Method
Hip	AB/AD	0.32	< 0.001*	0.26
	IN/EX	0.01*	< 0.001*	0.15
	FL/EX	0.22	< 0.001*	0.29
Knee	AB/AD	0.14	< 0.001*	0.16
	IN/EX	0.01*	0.0016*	0.28
	FL/EX	0.10	< 0.001*	0.02*
Ankle	AB/AD	0.19	0.01*	0.31
	IN/EX	0.28	0.03*	0.03*
	FL/EX	0.43	0.001*	0.42
Hip	Antero-posterior (X)	0.49	0.45	0.83
	Longitudinal (Y)	0.49	0.02*	0.19
	Medio-lateral (Z)	0.08	0.001*	0.02*
Knee	X	0.33	0.002*	0.65
	Y	0.18	< 0.001*	0.06
	Z	0.11	0.003*	0.15
Ankle	X	0.13	0.006*	0.19
	Y	0.70	0.80	0.89
	Z	0.56	< 0.001*	0.14

Note) *significant at 0.05.

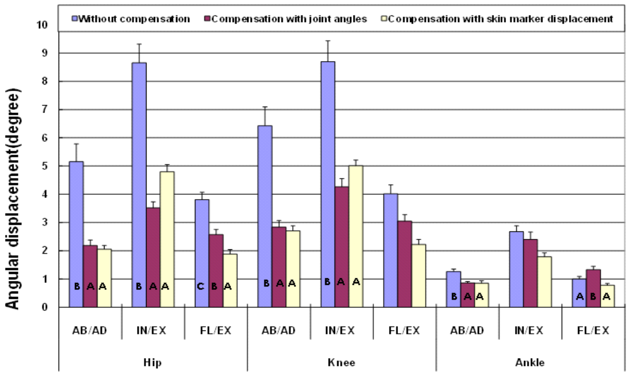


a) Walking

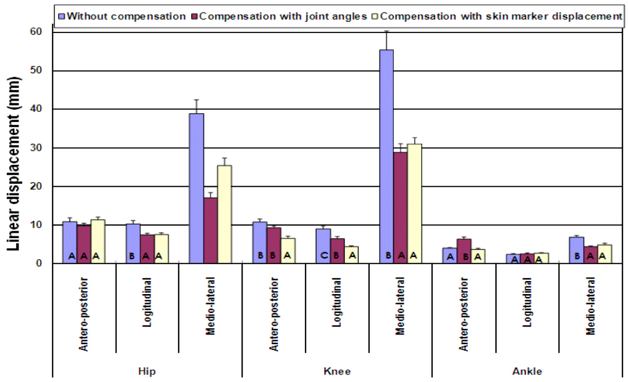


b) Sit-to-stand/stand-to-sit

<Figure 3> Differences between Two Angular Motions Estimated Using Two Different Marker Clusters for a Participant (Compensation with Skin Marker Displacement : Solid Black; Compensation with Joint Angle : Dashed Black; without Compensation : Solid Gray)



a) Angular motion



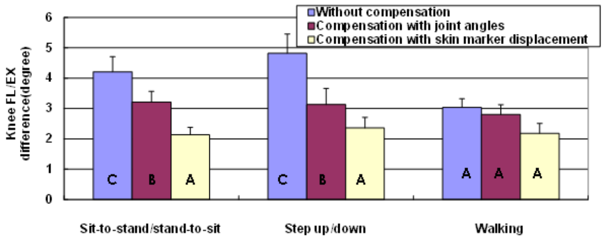
b) Linear motion

<Figure 4> SNK Test of the Mean Differences for Different Analysis Methods (Significance Level 0.05)

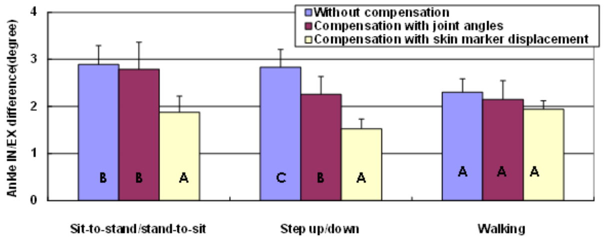
The student Newman-Keuls (SNK) test of the mean differences for the three methods showed that compensation with skin marker displacement was more effective than without compensation for most kinematic variables, and more effective than compensation with joint angle for some of them. For most angular joint motions, compensation with skin marker displacement had significantly smaller (33~60%) mean differences than without compensation, except for ankle flexion/extension (see <Figure 4>(a)). Compensation with skin marker displacement had significantly smaller mean differences than compensation with joint angle for the flexion/extension of the hip and ankle (27 and 41%, respectively). For knee flexion/extension and ankle internal/external rotation where the interaction effect existed, compensation with skin marker displacement had significantly smaller mean differences than without compensation and compensation with joint angle in sit-to-stand/stand-to-sit and step up/down motions, but not in walking (see <Figure 5>).

Moreover, compensation with skin marker displacement had significantly smaller (27~52%) mean differences than without compensation for five of the nine linear motions: hip and knee longitudinal, knee and ankle medio-lateral, and knee antero-posterior displacements (see <Figure 4>(b)). It also had significantly smaller (30~42%) mean differences than compensation with joint angle for three motions: knee antero-posterior and longitudinal, and ankle antero-posterior displacement (see <Figure 4>(b)). For hipmedio-lateral motion where the interaction effect existed, compensation with skin marker displacement had significantly smaller differences than without compensation, but had significantly larger mean differences than compensation with joint angle in walking and step up/down motions (see <Figure 6>).

In summary, compensation with skin marker displacement had significantly less difference by 27~42% compared to the compensation method with joint angle in seven kinematic variables : hip, knee and ankle flexion/extension, ankle internal/external rotation, knee antero-posterior and longitudinal displacement, and ankle antero-posterior displacement.

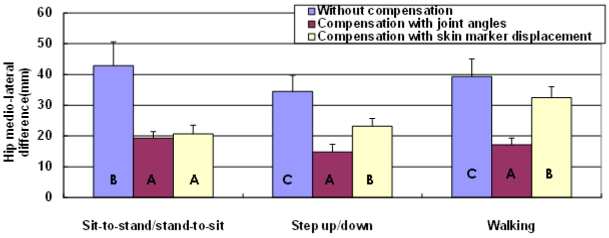


a) Knee FL/EX



b) Ankle IN/EX

<Figure 5> SNK Test of the Mean Differences of Knee FL/EX and Ankle IN/EX (Significance Level 0.05)



<Figure 6> SNK Test of the Mean Differences of Hip Medio-Lateral Motion (Significance Level 0.05)

4. Discussion and Conclusions

Both AL compensation methods (with skin marker displacement and joint angle) were effective in reducing the STA errors of hip and knee joints in real lower extremity motions. In the study, differences between two marker clusters for the hip and knee kinematic variables (all but hip antero-posterior motion) were significantly reduced by 30~60% by AL compensation with skin marker displacement compared to that without compensation. Reduction of errors by AL compensation with joint angle ranged from 10~60% (see <Figure 4>).

Of the two AL compensation methods, the one using skin marker displacement was slightly more effective in analyzing lower extremity motions. Results showed that the differences of five kinematic variables (hip FL/EX, ankle FL/EX, knee antero-posterior, knee longitudinal, and ankle antero-posterior motion) were significantly reduced by compensation with skin marker displacement by 30~40% more than joint angle compensation regardless of the target motion. The former method also significantly reduced the differences of knee FL/EX and ankle IN/EX in sitting and stepping than the latter method by 25~30%. Compensation with joint angle was 35~50% more effective than skin marker displacement in significantly reducing differences of only one variable (hip medio-lateral motion) in some target motions.

Compensation with joint angle had some limitations in analyzing the kinematics of the ankle joint. While compensation with joint angle was as effective as with skin marker displacement in analyzing hip and knee joint motions, it had larger mean differences than without compensation for some variables of the ankle joint. This ineffectiveness seems to be because of the relatively large inaccuracy of the joint angle used in AL compensation. Without compensation, the mean difference of knee FL/EX was as large (4.0°) as that of hip FL/EX (3.8°); the joint angle estimated without compensation was used to estimate AL positions in compensation with joint angle. In contrast, AL displacements of the shank (5~20 mm) were small relative to those of the thigh (15~40 mm). Therefore, the inaccurate knee joint angle seems to have a large effect on the AL position estimation of the shank relative to the thigh.

Neither compensation with skin marker displacement nor compensation with joint angle solved the STA errors completely; residual errors still exist. Even in a stationary posture, mean differences between two sets of kinematic variables estimated using two marker clusters, which represent the instrumental errors in this study, were 0.1~3° and 1~16 mm for angular and linear motions, respectively. During target motions, mean differences for compensation with skin marker displacement and compensation with joint angle were 1~5° and 5~30 mm for angular and linear motions, respectively.

Compensation with skin marker displacement reduced the motion analysis STA errors more reliably than with joint angle, although both methods were superior to without compensation. For hip and knee motions, both AL compensation methods reduced differences between marker clusters by half in the three motions than without compensation (see <Figure 4>(a)). Compensation with joint angle had the weaknesses in analyzing ankle motion, whereas compensation with skin marker displacement consistently reduced the STA error of angle motion than without compensation. Therefore, this method can be reliably applied in motion analysis of lower extremities.

The following further studies would be necessary to advance this method. First, the various motions should be designed for dynamic calibration. This study only used hip joint motion with fixed knee and knee motion with fixed ankle. There are no motion for the dynamic calibration of pelvis and upper arms. In addition, because this method was tested with Korean, it should be tested with other people for its external validity.

Acknowledgement

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2012-0003457).

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