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Reproducibility of Knee Movement Analyses during the Stance Phase Using the Anatomical Landmarks Calibration

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Abstract. [Purpose] The purpose of this study was to verify the reproducibility within a session and between sessions of the knee joint movement and moment during the stance phase using the Anatomical Landmarks Calibration. [Subjects] The study subjects were five healthy adults. [Methods] The subjects walked along a 10-m walkway. Reflective markers were attached to each subject's anatomical landmarks on the right lower extremity. Moreover, rigid plates with three attached reflective markers were placed on the lateral side of the thigh and shank. The anatomical landmarks presumed by the thigh and shank clusters were used for the knee angle and joint moment calculations. To check the reproducibility of the joint angles and moments, coefficients of multiple correlations (CMCs) and standard errors of measurement (SEMs) were computed. [Results] The CMCs of abduction–adduction and internal–external rotation of the knee joint between sessions were lower than those within a session, while the SEMs were larger. Regarding the knee joint moment, all the subjects showed larger SEMs between sessions than within a session. [Conclusions] The present results suggest that it is important to identify the attachment positions of the reflective markers to obtain good reproducibility for knee joint angle changes.
Key words: Anatomical Landmarks Calibration, Reproducibility, Coefficient of multiple correlations

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INTRODUCTION

Gait analysis using a motion analysis system is a clinically important assessment method. Generally, an infrared reflective marker is stuck on a subject's skin surface, and the technique of recording its motion with some cameras is widely used[1–3)]. We need to use a set of at least three non-collinear reflective markers on each segment to define a rigid body in three-dimensional space. Accordingly, the marker positions are used generally anatomical landmarks that are comparatively easy to identify by palpation. On the other hand, when using a bone projection part as an anatomical landmark, it has been reported that each reflective marker stuck on the skin surface will move independently owing to modification of the soft tissue organization according to the shock in the early stance phase or the influence of muscle contraction[4)]. Therefore, when computing a joint angle and joint moment from anatomical landmarks, it is considered that many errors will arise in the measurement results.

To compensate for the faults of such skin markers, a method designated the Anatomical Landmarks Calibration (ALC), which involves two or three markers stuck on each segment and the anatomical landmarks presumed from the coordinate system of these two or three markers, has been reported[5–7)]. In addition, it is presumed that the markers stuck on a rigid plate excel in practicality and accuracy compared with skin markers[8)].

However, inaccurate sticking of the reflective markers to the anatomical landmarks by a tester can mislead the presumption of their positions when using the ALC, and the calculated joint angle and moment will be inaccurate as a result.

When a tester sticks reflective markers on anatomical landmarks identified by palpation, it is necessary to carry out the process carefully enough to identify each anatomical landmark. An error of measurement induced by the marker position has the possibility of confounding the interpretation of the result, and it is further thought that an examination of the reproducibility of measurements is important to improve the reliability of measurement results[9)].

The purpose of this study was to verify the reproducibility within a session and between sessions of the knee joint movement and moment during the stance phase.

SUBJECTS AND METHODS

The study subjects were five healthy adults (three males and two females; mean age ± SD, 28.2 ± 4.3 years; mean

Fig. 1. Rigid plates, the black squares, with three reflective markers attached to the thigh and shank.

height ± SD, 1.70 ± 0.17 m; mean mass ± SD, 66.0 ± 7.7 kg; mean BMI ± SD, 23.5 ± 2.4 kg/m^2) (Table 1), who had neither orthopedic disease of the lower limbs or spine nor neurological impairment, and did not have any limitations in their activities of daily life. All the subjects provided their written informed consent prior to assessment. Ethical approval for this study was obtained from the Ibaraki Prefectural University of Health Sciences Ethics Committee.

A three-dimensional motion analysis system (Vicon, Oxford, UK) and a floor-mounted force plate (Kistler Instruments, Winterthur, Switzerland) that each had a sampling rate of 200 Hz were used in this study. The subjects walked barefoot along a 10-m walkway at their self-selected habitual speeds and were directed to step on the force plate with the right lower limb. The number of trials was five, with sufficient rest between the trials. Reflective markers of 9.5 mm in diameter were attached with double-sided tape to each subject's pelvis and anatomical landmarks on the right thigh, shank and foot segments. After identification by palpation, the markers were directly placed over the following anatomical landmarks: bilateral anterior and posterior superior iliac spines, unilateral greater trochanter, lateral and medial femoral epicondyles, lateral and medial tibial condyles, lateral and medial malleoli, calcaneus and top of the foot at the base of the second metatarsal. Moreover, rigid plates with three attached reflective markers were placed on the lateral side of the thigh and shank (Fig. 1). After attachment of the markers, decisions were made for the relative positions of the anatomical landmarks of the two rigid plates for the ALC based on a single static calibration to estimate the anatomical landmarks of the thigh and shank from the ALC. The anatomical landmarks used for the thigh and shank clusters were the greater trochanter, lateral and medial femoral epicondyles, lateral and medial tibial condyles, and lateral and medial malleoli, and the coordinate values of their anatomical landmarks were used for the knee angle and joint moment calculations.

To examine the reproducibility of the measurements between sessions for each subject, the values were re-measured using the same procedure after about 1 week. One physical therapist with 10 years or more of experience performed the attachments of the reflective markers to the anatomical landmarks.

Foot-strike and toe-off were determined using the force plate data and the corresponding frame number was identified in the recorded images. The data were normalized to the stance phase (foot-strike to toe-off=100%) using spline interpolation. The knee joint angles during the stance phase were calculated using the joint coordinate system approach described by Grood et al.[10]. The joint moment is computed using the inverse dynamics technique. The center of gravity and mass of each segment, joint force of the knee, angular momentum of the shank, *et cetera* were calculated from the anatomical landmarks on the thigh and shank, which were derived from the ALC, and investigated for the knee moment using the following formulas:

$$F_k = m_s + F_a - m_s g$$

$$M_k = H_s + M_a + F_a(J_a - C_s) - F_k(J_k - C_s)$$

where F_k and F_a are the knee and ankle joint forces, respectively, m_s is the mass of the shank, g is the acceleration of gravity, M_k and M_a are the knee and ankle joint moments, respectively, H_s is the angular momentum of the shank, J_a and J_k are the knee and ankle joint centers, respectively, and C_s is the center of gravity of the shank. In addition, the body segment parameters used the presumed coefficients reported by Ae et al.[11].

To check the reproducibility of the waveform data for the joint angle and joint moment for each subject within a session and between sessions, the coefficient of multiple correlations (CMC) was computed according to the method of Kadaba et al.[12] as an index of relative reliability using the following formulas.

$$\text{Within CMC} = \sqrt{1 - \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}\left(Y_{ijt}-\bar{Y}_{it}\right)^2/MT(N-1)}{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}\left(Y_{ijt}-\bar{Y}_{i}\right)^2/M(NT-1)}}$$

where M is the number of test days, N is the number of the trials, T is the number of the data points, Y_{ijt} is the *t*th time point of the *j*th run on the *i*th test day, $\bar{Y}_{it}$ is the average at time point *t* on the *i*th test day, $\bar{Y}_{i}$ is the mean on the *i*th day.

$$\text{Between CMC} = \sqrt{1 - \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}\left(Y_{ijt}-\bar{Y}_{t}\right)^2/T(MN-1)}{\sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}\left(Y_{ijt}-\bar{Y}\right)^2/(MNT-1)}}$$

where $\bar{Y}_t$ is the average at time point *t* over MN gait cycles, and $\bar{Y}$ is the mean over time.

Furthermore, in each subject's stance phase, to check how much error of the angle and moment appeared at the time

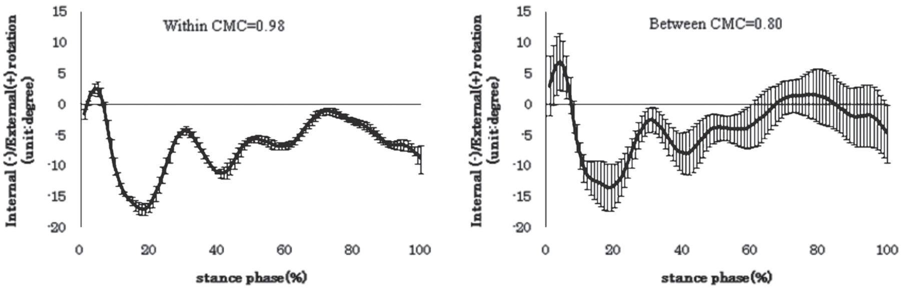

Fig. 2. Representative data of CMCs within a session and between sessions for the external-internal rotation angle of Subject 2. The vertical bars show the SD.

Table 1. Characteristics of the subjects

Subjects	SEX	AGE	height (m)	weight (kg)	BMI (kg/m^2)
1	female	33	1.62	70	26.7
2	male	26	1.78	66	20.8
3	male	29	1.77	73	23.3
4	female	22	1.56	53	21.8
5	male	31	1.68	68	25.0
AVE		28.2	1.68	66.0	23.5
SD		4.3	0.11	7.7	2.4

Table 2. Coefficient of multiple correlations (CMC) within a session for each subject

	knee joint angle			knee joint moment		
	flex-ext	abd-add	ext-int	flex-ext	abd-add	ext-int
Subject 1	0.96	0.83	0.90	0.99	0.83	0.80
Subject 2	0.99	0.92	0.98	0.99	0.98	0.98
Subject 3	0.94	0.91	0.97	0.98	0.96	0.93
Subject 4	0.98	0.97	0.90	0.99	0.98	0.76
Subject 5	0.95	0.80	0.97	0.98	0.96	0.97

Table 3. Coefficient of multiple correlations (CMC) between sessions for each subject

	knee joint angle			knee joint moment		
	flex-ext	abd-add	ext-int	flex-ext	abd-add	ext-int
Subject1	0.96	0.81	0.81	0.99	0.80	0.83
Subject2	0.98	0.80	0.80	0.99	0.94	0.97
Subject3	0.97	0.83	0.83	0.98	0.76	0.95
Subject4	0.98	0.87	0.81	0.99	0.97	0.82
Subject5	0.96	0.84	0.82	0.98	0.85	0.86

when the standard deviation was the largest, the standard error of measurement (SEM) was computed as an index of quantitative reliability[13].

RESULTS

The CMCs within a session and between sessions for the knee joint movement and moment for each subject are shown in Tables 2 and 3, respectively. The values ranged from 0.76 to 0.99 for all the knee joint movements and the moments within a session. Although the average knee joint movement and moment of flexion–extension ranged from 0.96 to 0.99 between sessions, the knee joint movement and moment of abduction–adduction and internal–external rotation showed

Table 4. Standard error of measurement (SEM) of the knee joint angle within a session for each subject

	knee joint angle (degrees)		
	flex-ext	abd-add	ext-int
Subject 1	2.89	2.32	3.74
Subject 2	3.43	1.20	1.60
Subject 3	6.96	1.97	1.60
Subject 4	2.32	1.06	1.79
Subject 5	2.44	1.70	2.53

Table 5. Standard error of measurement (SEM) of the knee joint moment within a session for each subject

	knee joint moment (Nm/kg)		
	flex-ext	abd-add	ext-int
Subject 1	0.25	0.05	0.07
Subject 2	0.16	0.04	0.06
Subject 3	0.11	0.04	0.13
Subject 4	0.09	0.03	0.08
Subject 5	0.11	0.03	0.06

Table 6. Standard error of measurement (SEM) of the knee joint angle between sessions for each subject

	knee joint angle (degrees)		
	flex-ext	abd-add	ext-int
Subject 1	0.78	1.23	4.53
Subject 2	3.74	4.21	4.67
Subject 3	4.84	4.76	7.12
Subject 4	1.99	4.23	7.52
Subject 5	4.74	6.93	5.79

Table 7. Standard error of measurement (SEM) of the knee joint moment between sessions for each subject

	knee joint moment (Nm/kg)		
	flex-ext	abd-add	ext-int
Subject 1	0.34	0.08	0.04
Subject 2	0.28	0.29	0.21
Subject 3	0.34	0.56	0.12
Subject 4	0.48	0.41	0.16
Subject 5	0.27	0.08	0.18

lower values than flexion–extension and ranged from 0.76 to 0.97. The CMCs within a session and between sessions for the external-internal rotation angle of Subject 2 are shown as representative data in Figure 2.

The SEMs with the largest standard deviation in the stance phase of the knee joint movement and moment within a session and between sessions are shown in Tables 4–7, respectively. The SEMs of the knee joint movement were larger between sessions than within a session, and the largest difference was the value of 7.52 degrees for internal–external rotation between sessions. Moreover, within a session, the flexion–extension of Subject 3 showed a rather large value of 6.96 degrees. Regarding the knee joint moment, almost all the subjects showed a larger SEM between sessions than within a session.

DISCUSSION

In this study, to confirm the reliability of the measuring method of the ALC, we examined the reproducibility of the measurements within a session and between sessions. The calculations of the knee angle and moment using the ALC were performed by assuming the anatomical landmarks in the stance phase of gait, based on the relative spatial relationships of the three markers on the rigid plates and the anatomical landmarks obtained in the static standing position. Therefore, to improve the reliability of the measurements, the attachment of the reflective markers on a subject requires good technique and experience in correctly palpating the anatomical landmarks[14)].

In this study, the reproducibility of the knee angle changes in the stance phase was comparatively good. However, the CMCs of abduction–adduction and internal–external rotation were a little inferior to that of flexion–extension movement between sessions. The movements of abduction–adduction and internal–external rotation were small compared with the flexion–extension movement, and since the CMC value should be dependent on the waveform, we think that the movements of abduction–adduction and internal–external rotation were slightly lower than the flexion–extension movement because the waveform varied within a narrow range.

Between sessions, the CMCs of abduction–adduction and internal–external rotation were lower than those within a session, and the SEMs were larger. We consider this to be the result of the influence of errors in the attachment positions of the reflective markers between sessions. Although determination of the right-and-left axis of the thigh and the long axis of the shank is important for the knee angle calculation method of Grood et al.[10)], the right-and-left axis of the thigh is determined by the vector that connects the lateral and medial epicondyles of the femur, meaning that errors in the attachment positions of the reflective markers to the lateral and medial epicondyles of femurs greatly influence the subsequent calculations. Since the lateral and medial epicondyles of the femur do not project like the lateral malleolus or fibula head, and are roundish compared with other anatomical landmarks, they are difficult to identify. Although the anatomical landmarks were also identified by palpation in this study, the errors of measurement were larger between sessions than within a session for abduction–adduction and external–internal rotation.

Although the knee joint moment during the stance phase of gait showed relatively good reproducibility within a session and between sessions, the SEMs of the knee joint moment were larger between sessions than within a session, and the

CMCs were a little inferior for the abduction–adduction moment and external–internal rotation moment than that for the extension–flexion moment. Since the knee joint moments of the frontal plane and horizontal plane during the stance phase are much smaller than that of the sagittal plane, the errors were large within a narrow range and, as a result, the CMCs and SEMs, depending on the degree of agreement of the wave pattern, would have shown low values. The errors between sessions for the knee joint moment were thought to arise because of the differences in the attachment positions of the reflection markers, similar to the case for the joint angle changes. Previous studies have reported that the value of the knee abduction–adduction moment is an important index for patients with osteoarthritis of the knee in gait analysis[15, 16]. As the CMCs and SEMs were lower between sessions for the abduction–adduction moment and external–internal rotation moment in the present study, we consider it necessary to carefully interpret the results provided by the measurements.

The limitations of this study were that the attachments of the reflective markers to the anatomical landmarks was performed by one physical therapist and that the repeatability between the examiners was not examined. In addition, the number of participants, five persons, was few.

We assume that the differences in positioning reflective markers on the body are large in the case of examiners with little experience, and it will be necessary to examine the repeatability of the measurements between examiners based on differences in their experience. In addition, for the interpretation of clinical data for osteoarthritis of the knee, it will be necessary to examine the analyses for both elderly people and young adults. Because the SEM was large between sessions, we suggest that it is important to carefully identify the attachment positions of the reflection markers to obtain repeatability of the knee joint angle changes. In addition, since the CMCs of abduction–adduction and external–internal rotation moment were slightly inferior to that of the flexion–extension moment, we think that it is necessary to carefully interpret the results provided by the measurements because the measurement method used in this study cannot provide the results of following the motion of a true bone and true values cannot be calculated.

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