Evaluation of dynamic knee joint alignment using a one-way frontal video method

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Abstract

In clinical practice, motion analysis can be challenging due to lack of space. Therefore, we propose a method of using one-way frontal video that can be executed easily in a small area. As it has been suggested that gait analysis using one-way frontal video can be used to analyze dynamic changes to knee joint alignment, the purpose of this research was to evaluate this method of motion analysis and examine the accuracy of this technique compared with that of a 3D motion analysis system. Twelve healthy subjects wearing optical reflective markers participated in this gait analysis study that involved the simultaneous use of one-way frontal video and a 3D motion analysis system. The femoral tibial angle (FTA) and the distance between the lower limb mechanical axis and the center of the knee joint were analyzed. The mean absolute error (MAE) of the results from the one-way frontal video and the 3D motion analysis system was calculated and the accuracy of the one-way frontal video method was evaluated. As a result, the patterns of change in knee alignment index obtained from the one-way frontal video all qualitatively matched those observed using the 3D motion analysis system. The MAE was 0.8 degrees in the FTA and the distance between the lower limb mechanical axis and the center of the knee joint was 2.5 mm. The MAE of knee joint alignment was sufficiently small compared to the alignment change associated with abnormal motion in patients with osteoarthritis. Therefore, the evaluation of knee joint alignment using the one-way frontal video method offers sufficient levels of accuracy to be used in diagnoses of abnormal movement.

Keywords : Frontal video, Gait analysis, Knee joint alignment, Femoral tibial angle, Lower limb mechanical axis

1. Introduction

In clinical settings such as orthopedic and rehabilitation centers, the objective observation of movement and an understanding of abnormal movement by doctors and physical therapists play major roles in making diagnoses. When evaluating human movement quantitatively, motion analysis is often performed using a 3D system that uses optical reflection markers and multiple cameras. In particular, the 3D motion analysis system is used to evaluate walking motion in assessing activities of daily living. For example, the kinematic evaluation of knee joint (Andriacchi et al., 1998; Ino et al., 2015), center of gravity evaluation (Whittle, 1997; Cotton et al., 2011), gait analysis of patients with knee joint diseases such as osteoarthritis (Kaufman et al., 2001; Phinyomark et al., 2016) and anterior cruciate ligament injury (von Porat et al., 2007; Takeda et al., 2014), and motion analysis in patients with hip joint diseases (Nankaku et al., 2005) have been reported. Gait analysis can objectively and quantitatively evaluate abnormal gait and provide effective basic data that can be used to establish appropriate forms of treatment and rehabilitation. However, when performing gait analysis using a 3D motion analysis system, an expensive dedicated setup and a large measurement space are required in order to place multiple cameras so that moving patients can continually be photographed. In practice, it is extremely difficult to secure enough space for this type of gait analysis in clinical settings such as hospitals.

Motion analysis using Microsoft Kinect has been actively studied as an inexpensive tool for use in clinical practice

(Schmitz et al., 2014; Eltoukhy et al., 2017; Asaeda et al., 2018). Schmitz et al. (2017) evaluated the accuracy of motion analysis using Kinect compared to a 3D motion analysis system in assessing the movement of lower limb joints during the star excursion balance test and Kinect was reported to have the same capabilities as the 3D motion analysis system. However, the error in the reach distance was found to be 0.80_2.07 cm and that in the joint angle was 2.04_5.74 degrees and these errors are larger than expected. Additionally, although the use of Kinect is inexpensive, a dedicated system is required.

We therefore proposed a one-way frontal video method of analyzing motion that can be executed easily in a small space (Kawakami et al., 2016). The proposed method analyzed abnormal motion using a moving image of a patient walking toward the camera using a single home video camera without the need for a dedicated device. In that report, the sway of the trunk center of gravity and the trunk tilt obtained by the gait analysis using the one-way frontal video qualitatively matched the results obtained using a 3D motion analysis system. It was suggested that dynamic changes to knee joint alignments could be analyzed using gait analysis in the same way when assessing the abnormal movement of osteoarthritic (OA) knees. However, that report did not consider the accuracy of evaluating knee alignment using the one-way frontal video method and it is necessary to examine the accuracy of the measurements in order to use the system in clinical practice.

The evaluation of knee joint alignment is generally performed to determine the status of OA knees (Brouwer et al., 2007; Matsumoto et al., 2015) and is used as an index of high tibial osteotomy (Dugdale et al., 1992; Kawakami et al., 2004). Usually, knee joint alignment is evaluated two-dimensionally, based on the femoral tibial angle (FTA) and where the lower limb mechanical axis, also called the loading axis or Mikulicz line, passes through the knee joint on an X-ray image taken in a static standing position. In terms of evaluating dynamic knee alignment several groups of researchers (Nishino et al., 2015; Kawakami et al., 2005) have investigated the lower limb mechanical axis during walking using 3D motion analysis and bone model analysis. Nishino et al. (2015) reported changes in the movement of the lower limb mechanical axis associated with the lateral thrust of the OA knee. If dynamic knee alignment could be evaluated easily during exercise, it would be possible to obtain useful data for treating knee joint diseases and understanding the patients' conditions.

The purpose of this research was to evaluate dynamic changes in knee joint alignment by motion analysis using one-way frontal video and to examine the accuracy of this method compared with that of a 3D motion analysis system. We evaluated accuracy by measuring healthy gait motion using the one-way frontal video and 3D motion analysis systems simultaneously and comparing the obtained measurements of knee joint alignment. The two knee joint alignment indices evaluated were dynamic FTA change and the distance D_{KC} between the lower limb mechanical axis and the center of the knee joint.

2. Gait analysis

2.1 Marker location and experimental setting

Gait analysis was performed on 12 healthy males aged 21.2 ± 3.4 years without disabilities in the lower limbs. As shown in Fig. 1, optical reflective markers were attached to the subjects' body at 12 points: anterior superior iliac spine (ASIS), greater trochanter, medial and lateral plateau, and medial and lateral malleolus on both lower limbs. The reflective markers were spherical, with a diameter of about 13 mm.

Figure 2 shows the installation status of the video camera and 3D motion analysis system. Measurements were taken during normal walking toward the camera and the walking speed was arbitrarily determined by each subject. A straight walking path with a length of 9 m was set and a square serving as the measurement reference position was drawn at the center of the walking path. A video camera (HDR-CX series, Sony Corp.) was installed at a location 5 m from the reference position. The height of the video camera was set to 0.9 m so that it was the same height as the subjects' ASIS, referring to the report by Kawakami et al. (2016). For the 3D motion analysis system (MAC3D System, nac Image Technology Inc.), eight infrared cameras were used and measurements were taken simultaneously with the video camera, as shown in Fig. 2. The frame rate of the captured video was 30 fps and the resolution of 1920×1080 pixels. The measurement sampling frequency of the 3D motion analysis system was 120 Hz.

The task was explained to the subjects with the approval of the ethics committee of the National Institute of Technology, Hakodate College and the measurements were taken with the consent of the participants.

Fig. 1 Optical reflective marker location. The reflective markers were a spherical in shape with a diameter of about 13 mm and were attached to 12 points on each subject: ASIS, greater trochanter, medial and lateral plateau, and medial and lateral malleolus on both lower limbs.

Fig. 2 Experimental setup for gait analysis. A square for the measurement reference position was drawn at the center of a 9 m long straight walking path. The video camera was installed at a height of 0.9 m at a position 5 m away from the reference position that took measurements simultaneously with the 3D motion analysis system, which used eight infrared cameras.

2.2 Magnification correction for one-way frontal video

Using the one-way frontal video method (Kawakami et al., 2016), the size of the subject varies with time on the video screen to capture the subject walking toward the camera. In this section, we explain how to correct the size of the subject captured in each frame of the video.

Fig. 3 The reference posture for correction of magnification in the frontal video is that of an upright stance facing toward the camera. The reference position is on one side of the reference rectangle.

As shown in Fig. 3, the reference posture, an upright stance facing toward the camera on one side of the reference position rectangle, was photographed. Video analysis software (Dartfish 6.0, Dartfish Japan Co., Ltd.) was used to analyze marker coordinate values of the reference posture and each frame image of the frontal video. The coordinates of the ASIS marker and reference rectangle vertices C_0 to C_3 were obtained in the x and z directions on the reference posture photograph, as shown in Fig. 3. In addition, the coordinates of each marker were acquired from each image in the frontal video. All of the pixel coordinate values were converted to coordinate values in mm units so that the length (L_0) of the side of the rectangle in which the subject stood was 0.8 m, which equated with the actual length.

To correct the magnification, the distance (l_0) between the ASIS measurements was calculated from the ASIS marker coordinate values at the reference position. The distance (l_i ; i = frame number) between the ASIS measurements during walking in each frame was calculated from the ASIS coordinate values obtained from the frontal video. From the ratio of l_0 and l_i , the magnification (H_i) of each frame was calculated using Eq. (1). H_i represents the ratio of the subject's size in each frame based on the reference distance l_0 . By dividing the marker coordinate value in each frame by the magnification H_i , the coordinate value was corrected so that the size of the subject in each frame was the same as that at the reference position.

$$H_i = \frac{l_i}{l_0} \quad (i = 1, 2, 3, \dots) \quad (1)$$

In the frontal video, the position of the subject in depth varies with time, so the position of the origin coordinate on relative to the subject also changes from frame to frame. Therefore, as shown in Fig. 3, a straight line (A) parallel to the walking path was defined on the image. The equation to determine A is shown in Eq. (2) using the vertex coordinate values $C_0(x_{C0}, z_{C0})$ and $C_1(x_{C1}, z_{C1})$ of the sides of the reference rectangle.

$$z = \frac{z_{C1} - z_{C0}}{x_{C1} - x_{C0}} x + \frac{x_{C1} z_{C0} - x_{C0} z_{C1}}{x_{C1} - x_{C0}} \quad (2)$$

The lengths L_0 and L_1 of the front and back sides of the reference rectangle on the walking path were calculated from the coordinate values of the vertices C_0 to C_3 , respectively, and the reference magnification h was obtained using Eq. 3. From the magnification H_i of each frame obtained using Eq. (1), the reference magnification h of the side of the reference rectangle, and the coordinate values of the points C_0 and C_1 on the straight line A , in each frame, Eq. (4), which represents the relationship between the magnification H_i and the x_i coordinate on A was derived.

$$h = \frac{L_1}{L_0} \quad (3)$$

$$x_i = \frac{x_{C0} - x_{C1}}{1 - h} H_i + \frac{x_{C1} - h x_{C0}}{1 - h} \quad (i = 1, 2, 3, \dots) \quad (4)$$

By substituting x_i obtained from Eq. (4) into Eq. (2) to obtain z_i , the coordinate values (x_i, z_i) on line A that serve as the reference origin for each frame were calculated. The reference origin coordinates (x_i, z_i) of each frame are the same as the relationship between the reference posture and the origin, C_0 , shown in Fig. 3. In each frame, the reference origin coordinates (x_i, z_i) were corrected for magnification in the same way as the marker coordinates; then the coordinate origin was corrected by subtracting the reference origin coordinates from each marker coordinate.

2.3 Definition of knee joint alignment and evaluation of accuracy

In this study, the coronal plane was defined as the plane perpendicular to the y-axis, which is the walking direction in the global coordinate system shown in Fig. 2. In the frontal video, the captured front image is a coronal plane. Two parameters were evaluated on the coronal plane for knee joint alignment using both gait analysis with the one-way frontal video and the 3D motion analysis system. The first parameter was the FTA and the second was the vertical distance, D_{KC} , between the mechanical axis of the lower limb and the center of knee joint. The center of hip joint, which was used to calculate these parameters, was defined with reference to the Clinical Gait Analysis Forum of Japan method (Kurabayashi et al., 2003), as shown in Fig. 4(a). On the line connecting the ASIS and the greater trochanter markers, point D was located 1/3 along the length d from the greater trochanter. The center of hip joint was defined as the point where D was inserted 60 mm along the line connecting the left and right ASIS. As shown in Fig. 4 (b), the center of knee joint was defined as the midpoint between the medial and lateral plateau markers and that of the ankle joint was defined as the midpoint between medial and lateral malleolus markers.

Fig. 4 Defining the centers of the (a) hip joint and (b) knee and ankle joints. The center of the hip joint was defined with reference to the Clinical Gait Analysis Forum of Japan method. The centers of the knee and ankle joints were defined as the midpoint of the medial and lateral markers.

Fig. 5 Definition of femoral tibial angle (FTA) and distance D_{KC} . The tibial and femoral axes were projected onto the coronal plane and the outer angle formed by the two axes was defined as the FTA. The vertical distance from the center of the knee joint to the lower limb mechanical axis was defined as the distance D_{KC} .

Figure 5 provides an overview of the FTA and distance D_{KC} , defined as the knee joint alignment. The line from the center of the knee joint to the center of the ankle joint was defined as the tibial axis and that from the center of the hip joint to the center of the knee joint was defined as the femoral axis. In each frame during walking, these two axes were projected onto the coronal plane and the outer angle formed by the two axes was defined as the FTA. In the defined FTA, angles over 180 degrees are varus and small angles are valgus. In the coronal plane, the segment between the center of the hip joint and the center of the ankle joint was defined as the lower limb mechanical axis and the vertical distance from the center of the knee joint to the lower limb mechanical axis was defined as the distance D_{KC} .

These knee joint alignments were calculated in the stance phase of the gait cycle (GC) and the results from the one-way frontal video were compared with those from the 3D motion analysis system. The stance phase was standardized as 60% of the GC and the mean values for approximately every 5% of the GC were compared using an unpaired t-test.

The errors for the FTA and distance D_{KC} were calculated using mean absolute error (MAE) and the accuracy of the results from the frontal video compared with the 3D motion analysis system was evaluated. MAE was calculated using Eq. (5).

$$MAE = \frac{1}{n} \sum_{j=1}^n |FTA_{3D_j} - FTA_{FV_j}| \quad (5)$$

Equation (5) uses FTA as an example. The symbol j is the time point for the frame obtained from the frontal video and the time synchronization between the two methods was analyzed by defining the time at which the synchronization marker started moving as time zero. FTA_{3D_j} is the FTA value obtained from the 3D motion analysis system and FTA_{FV_j} is the FTA value obtained from the one-way frontal video. The MAE for the distance D_{KC} was calculated in the same way as described above for the FTA.

The influence of rotation of the body segments, such as the pelvis and the femur, around the vertical axis were also considered to be one of the causes of the error. Therefore, the correlation between the rotation angle in the horizontal plane of the pelvis and the femur and the errors of the FTA and the distance D_{KC} was examined. The rotation angle of the pelvis was defined as the angle of the line connecting ASIS in the horizontal plane (counterclockwise is positive), and the rotation angle of the femur was defined as the angle in the horizontal plane of the line connecting the markers of the medial and lateral plateaus (the external rotation is positive). The errors of the FTA and distance D_{KC} were calculated as the difference between the result of the 3D motion analysis system and the result from the frontal video. Spearman's rank correlation coefficient was used to test the correlation.

3. Results

3.1 Knee joint alignment in the stance phase

Figure 6 displays the changes in FTA during the stance phase as measured using the one-way frontal video method and 3D motion analysis system. The horizontal axis of the graph depicts the GC; the stance phase was normalized to 60% of the GC. The vertical axis represents the FTA angle (results are provided as mean and one standard deviation). The FTA obtained using the one-way frontal video was 180.6 ± 3.0 degrees at the time of initial contact (0% GC) and that measured using the 3D motion analysis system was 180.9 ± 2.7 degrees. There was almost no change during the loading response, mid stance, and terminal stance. Following the initial contact, the FTA tended to increase during the pre-swing before toe-off (about 55% GC). Therefore, the results from the frontal video and the 3D motion analysis system were qualitatively consistent, and a similar trend was observed. In addition, there was no significant difference in the FTA calculated using each method at every 5% of the GC.

Fig. 6 The changes in the FTA during the stance phase. The FTA calculated from one-way frontal video and the 3D motion analysis system were qualitatively consistent. There was no significant difference in the FTA obtained using each method at every 5% of the GC.

Fig. 7 The changes of the distance, D_{KC} , during the stance phase. The distance, D_{KC} , calculated using the one-way frontal video and 3D motion analysis system were qualitatively consistent. There was no significant difference in the distance, D_{KC} , obtained using each method at every 5% of the GC.

Figure 7 shows the changes of the distance D_{KC} between the center of the knee joint and the lower limb mechanical axis in the stance phase as measured by each method. The horizontal axis of the graph represents the GC and the stance phase was normalized to 60% of the GC. The vertical axis represents the distance, D_{KC} , and positive values indicate the outside distance from the lower limb mechanical axis. The distance (D_{KC}) as calculated from the one-way frontal video, was 1.8 ± 11.2 mm at the time of initial contact (0% GC) and the measurement obtained using the 3D motion analysis system was 3.2 ± 10.1 mm. D_{KC} increased to about 8 mm during mid stance in both methods and further increased during pre-swing (about 55% GC). Similar to the change in the FTA, the D_{KC} values obtained using the one-way frontal video and 3D motion analysis system were qualitatively consistent, and there was no significant difference in the distance, D_{KC} , measured by each method at every 5% of the GC.

3.2 Accuracy of knee joint alignment using one-way frontal video

In the frontal video image, the length range represented by one pixel during the stance phase of the analysis range was 1.9 mm to 2.7 mm.

Table 1 shows the MAE of the FTA and distance, D_{KC} , calculated as the error of the frontal video in terms of results from the 3D motion analysis system. Each MAE was calculated using all video frames in the stance phase analyzed from the frontal videos of 12 subjects. The MAE for the FTA was 0.8 degrees and that for the distance, D_{KC} , was 2.5 mm. The ratio of the MAE to the range of each mean index value in the stance phase was 10.1% for the FTA and 13.6% for the distance, D_{KC} .

Table 1 The mean absolute error in the measurement of knee joint alignment using the one-way frontal video method

Knee joint alignment	Mean absolute error
FTA	0.8 degrees
D_{KC}	2.5 mm

Table 2 shows the correlation coefficient between the rotation angle of the pelvis and the femur in the horizontal plane and the errors of the FTA and the distance D_{KC} . During the stance phase, the rotation angle of the pelvis was in the range of -13.3 to 8.4 degrees. The correlation coefficient between the rotation angle of the pelvis and the error of FTA was 0.32, and the correlation coefficient with the error of D_{KC} was 0.30. The rotation angle of the femur ranged from -15.3 to 20.4 degrees. The correlation coefficient between the rotation angle of the femur and the error of FTA was 0.20, and the correlation coefficient with the error of D_{KC} was 0.21. There was no strong correlation between the rotation angle of the pelvis and the femur in the horizontal plane and the error of the knee alignment index.

Table 2 The correlation coefficient between the rotation angle of the pelvis and the femur in the horizontal plane and the error of the knee joint alignment index.

	Error of FTA	Error of D_{KC}
Rotation angle of the pelvis	0.32	0.30
Rotation angle of the femur	0.20	0.21

4. Discussion

The knee joint alignment measured using the one-way frontal video was almost the same as that measured using the 3D motion analysis system; no significant difference was observed. These results indicate that gait analysis using the one-way frontal video to evaluate dynamic changes in knee joint alignment is equivalent to using the 3D motion analysis system. For example, a sudden change in knee joint alignment associated with an abnormal movement such as lateral thrust can be evaluated simply by taking a video from the front without performing extensive motion analysis.

As the MAE of the FTA was less than 1 degree, the measurement obtained using the one-way frontal video was considered to be of sufficient accuracy in comparison with the results obtained using the 3D motion analysis system. The MAE of the distance D_{KC} was a little larger than the change range. This position or distance error may be one of the limitations of this study. One of the causes of this error may be the difference in the depth position between the ASIS, which is the reference for the magnification correction, and the measurement limb. In walking, the lower limb moves in the front-rear direction compared to the reference, ASIS, so the magnification correction seems to contain some errors. However, according to the distance D_{KC} measurements for walking in OA patients with lateral thrust as reported previously, the range of change in OA patients was about 26.6 mm (Kawakami et al., 2016). This suggests that the MAE calculated in this study is sufficiently small compared to the range of change for distance D_{KC} in OA patients. Therefore, it is considered that a large alignment change such as lateral thrust in OA patients can be sufficiently analyzed even using the a one-way frontal video.

The influence of rotation of the body segments, such as the pelvis and the femur, around the vertical axis could also be a cause of the error. In the results, there was no strong correlation between the rotation angle of the pelvis and the femur in the horizontal plane and the error of the knee alignment index. Therefore, in the gait analysis using the one-way frontal video, the influence of pelvic and femoral rotation was considered to be small during the stance phase.

This research uses the pixel coordinates of the video image to track the markers and does not correct them. The size of the marker changes on the video image in the same way as the size of the subject changes. The number of pixels in the marker differs from frame to frame and, therefore, the same point on each marker cannot be tracked. This is considered also to be one of the error factors. This factor can be resolved by introducing image processing calculations such as determining the marker's center of gravity from the pixels in the marker.

Compared to the accuracy of motion analysis obtained by using Kinect, as reported by Schmitz et al. (2017), the accuracy of motion analysis using the one-way frontal video was sufficient. Although the measurement index differed between the 3D kinematics and knee joint alignment at the frontal plane, the accuracy was compared with the results obtained from the 3D motion analysis system. Therefore, we consider that the evaluation of knee joint alignment using the one-way frontal video technique, as well as the Kinect method, will be useful in clinical practice. Furthermore, motion analysis using one-way frontal video can be applied not only to the evaluation of knee joint alignment, but also to many other measurements such as body sway and tilt, center of gravity tracking, and hip joint angle, even though it is limited to the frontal plane (Kawakami et al., 2016). We think that this method can also be implemented on smartphones and tablet devices because abnormal movements can be detected just by taking a video from the front. Therefore, we believe that this method can be used by anyone without specialized systems or specialized knowledge and it can be applied in a variety of settings such as medical examination rooms, nursing homes, and residential homes.

5. Conclusion

In this study, in order to examine the accuracy of measuring dynamic knee joint alignment by motion analysis using a one-way frontal video method, we carried out measurements using the frontal video technique and a 3D motion analysis system simultaneously in healthy subjects. The measurements of knee joint alignment obtained using the one-way frontal video method were almost the same as those measured using the 3D motion analysis system. The MAE of the knee joint alignment values was sufficiently small compared to the alignment change associated with abnormal motion in OA patients. Therefore, the evaluation of knee joint alignment using the one-way frontal video is considered to be sufficiently accurate to diagnose abnormal movement.

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