

Accuracy Verification of 4D-CT Analysis of Knee Joint Movements: A Pilot Study Using a Knee Joint Model and Motion-capture System

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Abstract

Background

Four-dimensional CT(4D-CT) is an advanced imaging method with the ability to acquire kinematic and three-dimensional morphological information. Although its use for analysis of the six degrees of freedom in the knee is expected, its accuracy has not been reported. This study aimed to use the optical motion-capture method to verify the accuracy of 4D-CT analysis of knee joint movement.

Methods

One static CT and three 4D-CT examinations of the knee joint model were obtained. The knee joint model was passively moved in the CT gantry during 4D-CT acquisitions. 4D-CT and static CT examinations were matched to perform 3D-3D registration. An optical motion-capture system recorded the position-posture of the knee joint model simultaneously with the 4D-CT acquisitions. These results were used as the correct answer value, the position-posture measurements using 4D-CT were compared to these values, and the accuracy of the 4D-CT analysis of knee joint movements was quantitatively assessed.

Results

The position-posture measurements obtained from 4D-CT showed similar tendency to those obtained from the motion-capture system. In the femorotibial joint, the difference in the spatial orientation between the two measurements was 0.7 mm in the X direction, 0.9 mm in the Y direction, and 2.8 mm in the Z direction. The difference in angle was 1.9° in the varus/valgus direction, 1.1° in the internal/external rotation, and 1.8° in extension/flexion. In the patellofemoral joint, the difference between the two measurements was 0.9 mm in the X direction, 1.3 mm in the Y direction, and 1.2 mm in the Z direction. The difference in angle was 0.9° for varus/valgus, 1.1° for internal/external rotation, and 1.3° for extension / flexion.

Conclusions

4D-CT with 3D-3D registration could record the position-posture of knee joint movements with an error of less than 3 mm and less than 2° when compared with the highly accurate motion-capture system. Knee joint movement analysis using 4D-CT with 3D-3D registration showed excellent accuracy for in vivo applications.

Background

The prevalence of locomotor disorders is expected to increase with the aging of the global population. Elderly people with locomotor disorders may experience joint pain and require nursing care support, and locomotor disorders are reported to account for 12% of the "bedridden" cases. Knee osteoarthritis is a common locomotor disorder estimated to affect 24 million individuals, and its prevention and treatment are of substantial importance [1]. Surgical treatments such as total knee arthroplasty (TKA) have been performed for advanced knee osteoarthritis, and excellent results have been reported. However, some reports have also described TKA failure caused by infection, loosening, malalignment, patellofemoral issues, and instability [2–4].

Kinetically abnormal joint movement is involved in the progression of osteoarthritis and articular cartilage damage [5]. Therefore, accurate analysis of the six degrees of freedom of the knee joint is important for tracking the onset and progression of osteoarthritis and for assessing kinematic changes after medical interventions such as surgeries and rehabilitation. Several methods for evaluating dynamic knee joint movement have been reported to date, including the

motion-capture method and the 2D-3D matching method. Motion-capture systems that measure "positions of human bodies, animals, and objects" and "time-series movements of joints" have recently gained acceptance. These systems are classified into the "optical type," which is widely used, and the "non-optical type," which include mechanical motion-capture systems and magnetic systems. The principles of the optical motion-capture method were proposed by Rashid et al. [6 33] in 1980. In this method, reflective markers are attached to an object, and its coordinates are measured using a camera. Because of its high accuracy in detection of the position and degree of free movement of objects, attempts have been made to use this method to evaluate gross joint movement. However, this method may not necessarily show a high accuracy when applied to the knee joint, since there is a gap between the movements of bone and soft tissues (skin, subcutaneous fat, and muscle) [7–9]. Implantation of beads in the bone to reduce this gap has been attempted, although it is an invasive evaluation [10, 11].

The 2D-3D matching method is a technique for superimposing a projected image (2D data) created from 3D-CT (3D data) on an X-ray fluoroscopic image (2D data). This enables measurement of distances and angles in three axial directions, and it has been used in computer-assisted navigation systems for analysis of joint dynamics. This method enables highly accurate measurement of knee joint movement, especially for biplane analysis [10, 12–14]. However, evaluation of the patella with a few morphological features is difficult [15 11], necessitating an additional CT scan to obtain three-dimensional morphological information [15].

Recent improvements in the multi-row structure of CT systems have enabled acquisition of a wide range at high speed. Four-dimensional CT (4D-CT) adds a time axis to three-dimensional data and allows continuous CT imaging on a time-series basis. This method has widespread clinical application for assessments such as evaluation of blood flow dynamics [16–19]. In the field of orthopedic surgery, this method is expected to improve evaluations of joint dynamics and functions [20]. Unlike the 2D-3D matching method, 4D-CT can acquire three-dimensional morphological information as well as kinematic information. However, there are concerns about the accuracy of joint dynamics evaluations performed by 4D-CT due to the presence of motion artifacts and partial-volume effects [21]. In response to this concern, Oki et al. [22] reported a dynamic evaluation method using 3D-3D registration, which superimposes 3D-CT images created from static lower-limb full-length CT onto 4D-CT. However, no studies have been conducted to verify the position-posture evaluation accuracy of knee joint movement using 4D-CT.

We hypothesized that 4D-CT using 3D-3D registration would enable highly accurate analysis of knee joint movement. Thus, the purpose of this study was to use the optical motion-capture method to verify whether high-precision analysis of knee joint movement is possible with 4D-CT using 3D-3D registration.

Methods

A knee-joint model was used as the subject. The model was passively moved inside the gantry of the CT device, and 4D-CT data were obtained, which were matched with the static CT data of the entire knee joint model to perform 3D-3D registration. An optical motion-capture system was used to verify the accuracy of 4D-CT data with 3D-3D registration (Fig. 1).

Bone model creation

A human knee skeleton model, including the femur, tibia, and patella, was manufactured by the laminate-shaping method using ZPrinter150 (3D Systems, Inc., California, USA), yielding the same shape as "SAWBONES SKU: 1148-3" (Pacific Research Laboratories, Inc. Sawbones, WA, USA). Cushioning materials with a thickness of approximately 5 mm were taped to the articular surface of the tibial model and the patellofemoral joint of the femur model to mimic the articular cartilage. Rubber bands were attached to both ends (distal and proximal) of the patella model, with the distal

rubber band fixed to the anterior surface of the femoral model and the proximal rubber band to the anterior surface of the tibial model. Using this approach, the three bone models that constituted the knee joint were connected. Tracker pins with a diameter of 3 mm were placed in each bone model to attach the tracker used in the navigation system (Fig. 2).

CT acquisition

A 320-slice multidetector CT (Aquilion One, Canon Medical Systems, Otawara, Japan) was used for CT imaging. Table 1 shows the imaging parameters for static CT images and 4D-CT images. First, a static CT image of the entire knee joint model was taken in the extension position. Next, the femoral side was fixed to the table such that the center of knee joint movement was located at the center of the CT imaging range. With the CT gantry tilted at 30°, 4D-CT scans were obtained with a rotation time of 10.5 s while the knee joint model was passively flexed from 0° to 90° by an experimenter. A total of 1.5 cycles of flexion-extension movement were performed in approximately 10.5 s, with the obtained 4D-CT data consisting of 20 volume scans. During 4D-CT imaging, the position-posture of the knee joint model was concurrently recorded by the navigation system (Fig. 3). The entire process of CT imaging as described above was repeated 3 times.

Table 1
Scanning parameters for static CT and 4D-CT data acquisitions

	Gantry tilt (degrees)	Section thickness (mm)	Range (mm)	Tube potential (kV)	Effective mAs (mAs)	Rotation time (s)	Acquisition interval	CT Dose Index Volume (mGy)	Dose-length product (mGy-cm)
Static	0	1.0×40	1000	120	9	0.5	NA	0.7	49
4D-CT	30	0.5×160	160	80	87	0.5	Continuous	31.0	495.6

Surface reconstruction and reference axis

The 4D-CT images in DICOM format were imported into a 3D model construction software (N-View, Teijin-Nakashima Medical. Co., Ltd. Okayama, Japan), and 3D models of the femur, tibia, and patella, which will be referred to as the “4D-CT model” hereafter, were constructed for each of the 20 volume scan acquisitions. Similarly, 3D models of the femur, tibia, and patella, which will be referred to as the “static CT model” hereafter, were constructed from the static CT images along the entire length of the lower limbs of the knee joint model. Simultaneously, a reference axis was defined on the static CT model (Figs. 4). In the 4D-CT model, the coordinate system was set for each volume scan based on the reference axis.

3D-3D registration

The imaging range of 4D-CT can be as small as 16 cm wide. The center of the femoral head and the center of the ankle joint, which are the reference points on the functional axis, are outside the imaging range of 4D-CT. In addition, the reference axis for evaluating the position-posture needs to be re-established for each volume scan. Position-posture evaluation with the 4D-CT model alone can be inaccurate for these two reasons. Therefore, in this study, the reference axis defined in the static CT model was applied to the 4D-CT model by surface-matching the two models in order to calculate the accurate position-posture of the 4D-CT model. Surface matching was completed using a software for editing polygon meshes (GOM Inspect 2018, GOM GmbH, Braunschweig, Germany).

Precision validation

For each volume scan, the position-posture expressed in the femur model coordinate system was calculated with reference to the tibia model coordinate system as the "FT position-posture." Similarly, for each volume scan, the position-posture expressed in the femur coordinate system based on the coordinate system of the patella model was also calculated as the "PF position-posture." The position of each volume scan was determined by determining the positional relationship between the origins of the coordinate system between volume scans, and the posture was obtained by angle-resolving the "distortion" between the coordinate systems.

The position-posture measurement of the bone model by the CT-based Navigation System (N-navi, Teijin Nakashima, Co., Ltd.) was performed in synchronization with 4D-CT imaging. For measurements with the navigation system, the same CT model and alignment definition as those adapted for 3D-3D registration were used. This measurement of the position and orientation of the simulated bone by the navigation system facilitated comparison of the position and orientation calculated by 3D-3D registration with the same criteria. Since the navigation system used in this study had an error of 0.6 mm and within 1 deg according to a previous study [23], the position and orientation measurement by this navigation system was used as the correct answer value. In each 4D-CT volume scan, the difference in position and posture (coordinates, varus/valgus, internal rotation/external rotation, extension/flexion) from the navigation system was calculated. The same analysis was performed on each of the three acquisitions of CT data. The accuracy of position-posture evaluation by 4D-CT was verified by calculating the average of absolute value differences.

Results

Figure 5 shows one of the three temporal position-posture measurements of 4D-CT and the navigation system for the tibiofemoral joint (FT joint) (Fig. 5-a) and patellofemoral joint (PF joint) (Fig. 5-b). Figure 6 shows the difference in position-posture measurements between 4D-CT and the navigation system for the FT joint (Fig. 6-a) and PF joint (Fig. 6-b).

The position-posture obtained from 4D-CT showed similar tendency as that obtained from the navigation system. In the FT joint, the difference in spatial orientation between the two measurements was 0.7 mm in the X direction, 0.9 mm in the Y direction, and 2.8 mm in the Z direction. The difference in angle was 1.9° in the varus/valgus direction, 1.1° in the internal/external rotation, and 1.8° in the extension/flexion. (Fig. 6-a) In the PF joint, the difference between the two measurements was 0.9 mm in the X direction, 1.3 mm in the Y direction, and 1.2 mm in the Z direction. The difference in angle was 0.9° for varus/valgus, 1.1° for internal/external rotation, and 1.3° for extension/flexion. (Fig. 6-b)

Since the subject itself moved while the gantry rotated, the 4D-CT data exhibited a partial-volume effect and motion artifacts (Appendix 1). Therefore, some artifacts were included in the bone model constructed by the binarization method from this 4D-CT image. In particular, artifacts were most noticeable in the middle of the flexion and extension movements, which had a high movement speed, and the afterimage of movements was confirmed in the bone axis of the tibia, which showed the largest movement (Fig. 7).

Discussion

In the present study, knee joint movement of the bone model was analyzed by matching 4D-CT and static CT scans of the entire length of the lower limbs by using 3D-3D registration. In order to examine the analysis accuracy, this method was compared with the navigation system using high-precision optical motion capture. The findings revealed that this was a highly accurate method for evaluating knee joint movements, with an error of less than 3 mm and less than 2°.

To our knowledge, reports on the accuracy of 4D-CT have been primarily focused on radiotherapy [24–27]. Lee et al. validated the accuracy of 4D cone-beam CT for radiotherapy by using a phantom and reported that the error was less than 2 mm when the respiratory movement was up to 30 mm [21]. The present study is the first to analyze the accuracy of 4D-CT in the joint area, and it showed that this technique showed the same accuracy as it did in the evaluation of respiratory movement.

Several reports in the field of radiotherapy have referred to artifacts in 4D-CT, demonstrating that artifacts affect lung function imaging and tumor volume assessment [24–27]. A similar problem may affect 4D-CT of the bone joint area for evaluating joint movement. In this study, highly accurate evaluation was possible by performing 3D-3D matching. However, it is unclear whether joint motion was evaluated correctly in the previous reports that did not perform registration with static CT.

In assessments using 4D-CT, the imaging range is limited to the area around the knee joint, making the alignment of the entire lower limbs unclear. In addition, the reference axis for evaluating the position and orientation must be provided for each volume scan, which may introduce errors. To avoid these problems, we measured knee joint movement using 3D-3D registration, matching the static CT model of the full length of the lower limbs with 4D-CT in accordance with the method described by Oki et al. [22–14]. Conventional methods such as 2D-3D matching have been considered to be particularly difficult to analyze the patella in the dynamics of the knee joint [12]. However, 4D-CT enabled the position and posture of the patella to be determined from three-dimensional data, allowing measurements of the patellofemoral joint with the same high accuracy as the femoral tibial joint.

Various methods have been used for analysis of knee joint dynamics, and the accuracy of these methods has also been reported. However, while this study investigated the accuracy of analyzing passive ROM movement in the non-weight-bearing position, previous reports performed dynamic analysis during walking and running. Therefore, comparisons between the present and previous studies are difficult. In dynamic analysis using body surface markers, the deviation from the bone movement due to the movement of the skin is a major concern. Sati et al. [28–51] reported a 2–17 mm gap between skin and bone in medial and lateral femoral condyles. Therefore, high accuracy cannot be expected using this method. Another common method is to attach external markers directly to the bone using percutaneous pins. However, Holden et al. [29–52] reported an error of up to 10 mm and 8° using this method. Accuracy analyses using fluoroscopy have also been performed. Hoff et al. [13–7] achieved very high accuracy of 2.25 mm and less than 0.035°. However, this analysis method can only be applied to the knee in which the implant is inserted. The analysis of knee joint movement by 4D-CT in this study can be applied to patients who have not undergone knee joint surgery to receive implants. 4D-CT can be expected to yield high accuracy in evaluation of actual patients.

The matching error between the 4D-CT and CT models can be explained by the fact that the 4D-CT model includes the effect of movement, and that the navigation system used for reference also contains an error. Thus, the accuracy of analysis by 4D-CT can be improved by reducing the motion speed of knee joint movement.

This study had several limitations. First, this study involved experimental verification using a bone model, which evaluated the dynamics of passive motion in the non-weight-bearing position. Verification with actual clinical patients can be expected in future studies. However, conventional CT equipment only allows participants to be evaluated in the non-weight-bearing position, which is a major disadvantage in any study. Upright CT, which allows a patient to stand, has been recently developed at the research level. While evaluations in the weight-bearing position are expected to be facilitated by this new CT technique, clinical application of the new technology will take more time [30–45]. Therefore, it is meaningful to pursue a highly accurate joint dynamics evaluation method in a widely used device. Second, the navigation system using optical motion capture contained inherent errors, which may have affected the analysis accuracy of this study. This navigation system, which is also used in surgery, has been used in many studies

analyzing knee joint motion [31 54, 32 53] and was shown to be extremely accurate, with an error of 0.6° and within 1 mm, indicating only a minimal effect on the scale of knee joint movement [23]. However, there may be problems when using this technique for small joints, because small errors can have a relatively large effect in small joints when compared to large joints. Third, both 4D-CT and general CT examinations are associated with the risk of radiation exposure. To avoid this risk, patients' gonads should be protected and possible measures should be taken to reduce radiation exposure when the patients undergo CT examinations. Further studies should be made using an appropriate 4D-CT imaging protocol.

Conclusion

In this study, the accuracy of knee joint analysis using 4D-CT with 3D-3D registration was determined using the optical motion-capture system. This method showed excellent accuracy and could be used in vivo applications.

Abbreviations

TKA, total knee arthroplasty; 4D-CT, four-dimensional CT; FT, femorotibial; PF, patellofemoral; ROM, range of motion

Declarations

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and materials: Not applicable

Competing interests: Not applicable

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Authors' contributions:

Contributed equally to this work: Yuki Kato and Takuya Adachi.

Yuki Kato and Takuya Adachi were involved in study design and data interpretation.

Yuki Kato, Takuya Adachi, and Daii Kiyotomo were involved in the data analysis.

Yuki Kato mainly performed the experimental procedures.

Youichi Machida and Katsushige Kawamukai supported the experimental procedures.

All authors critically revised the report, commented on drafts of the manuscript, and approved the final report.

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Figures

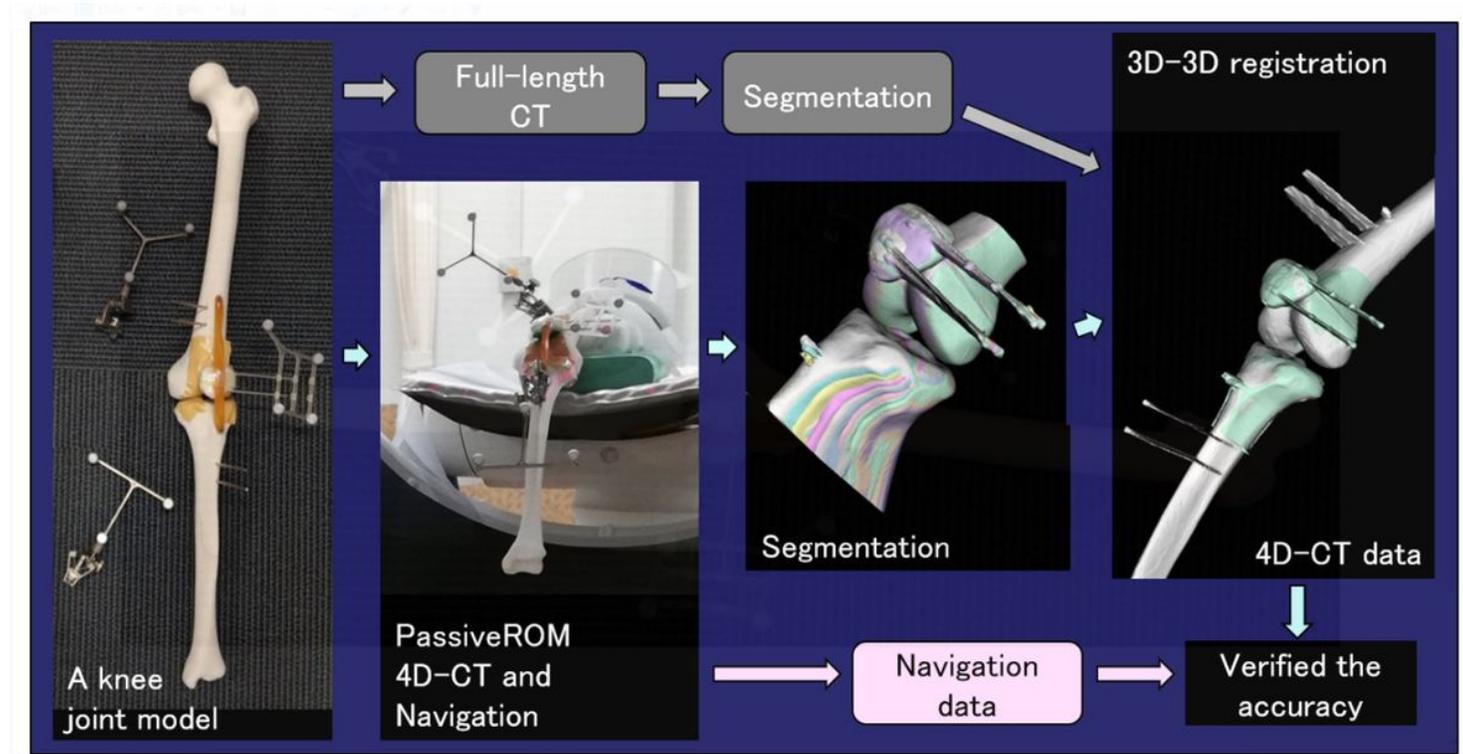


Figure 1

Process flow from CT acquisition to dynamic analysis.

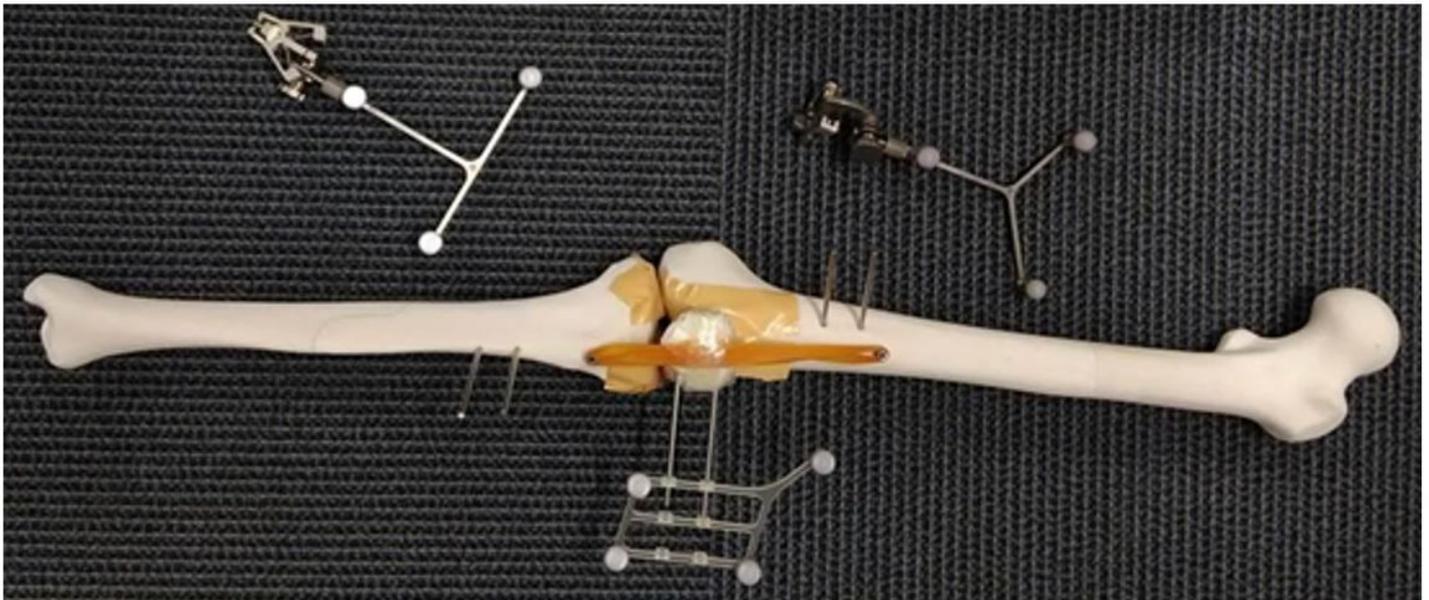


Figure 2

Human knee skeletal bone model. The bone models were connected with rubber bands, and two tracker pins were attached to each bone model for the navigation system.

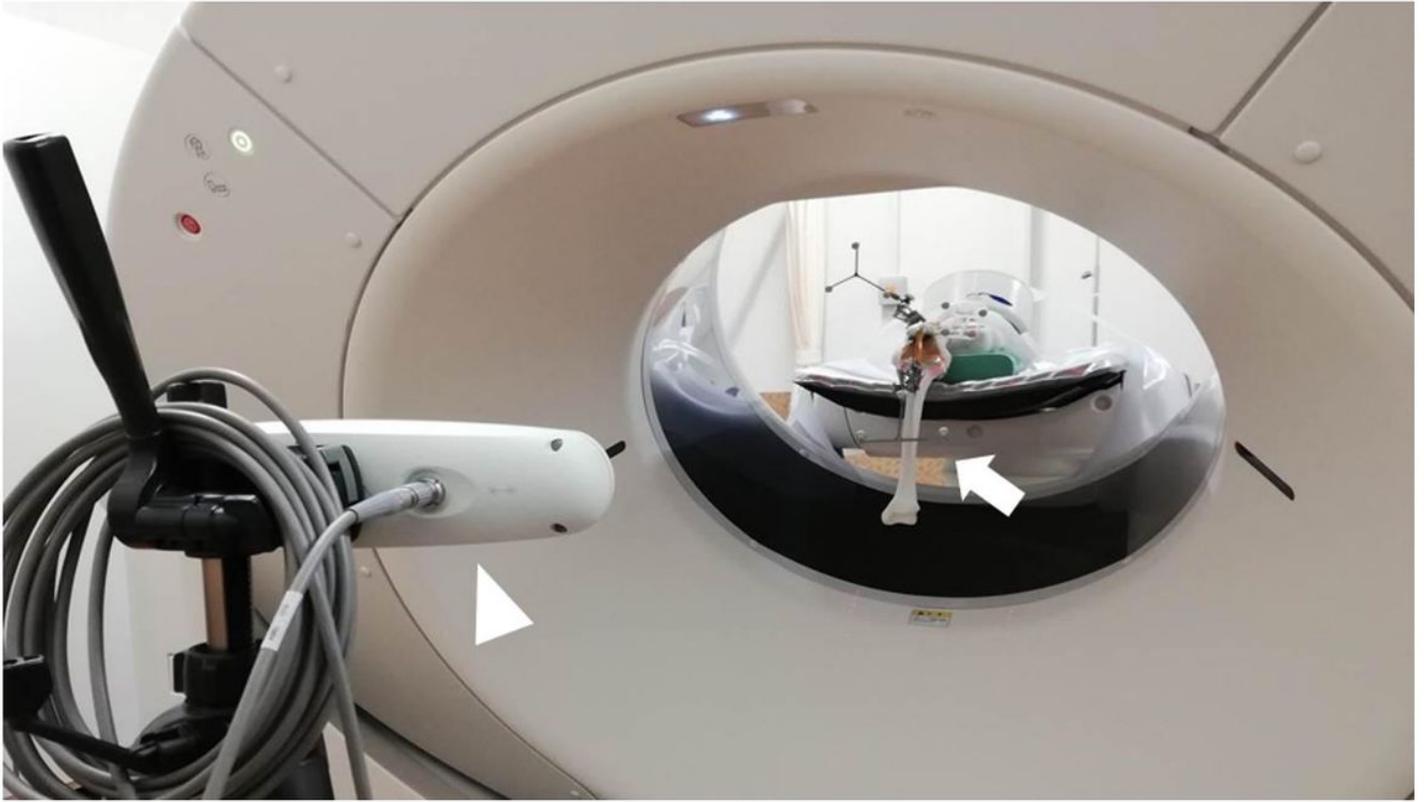


Figure 3

Knee joint model in the CT gantry (arrow) and the navigation system (arrowhead).

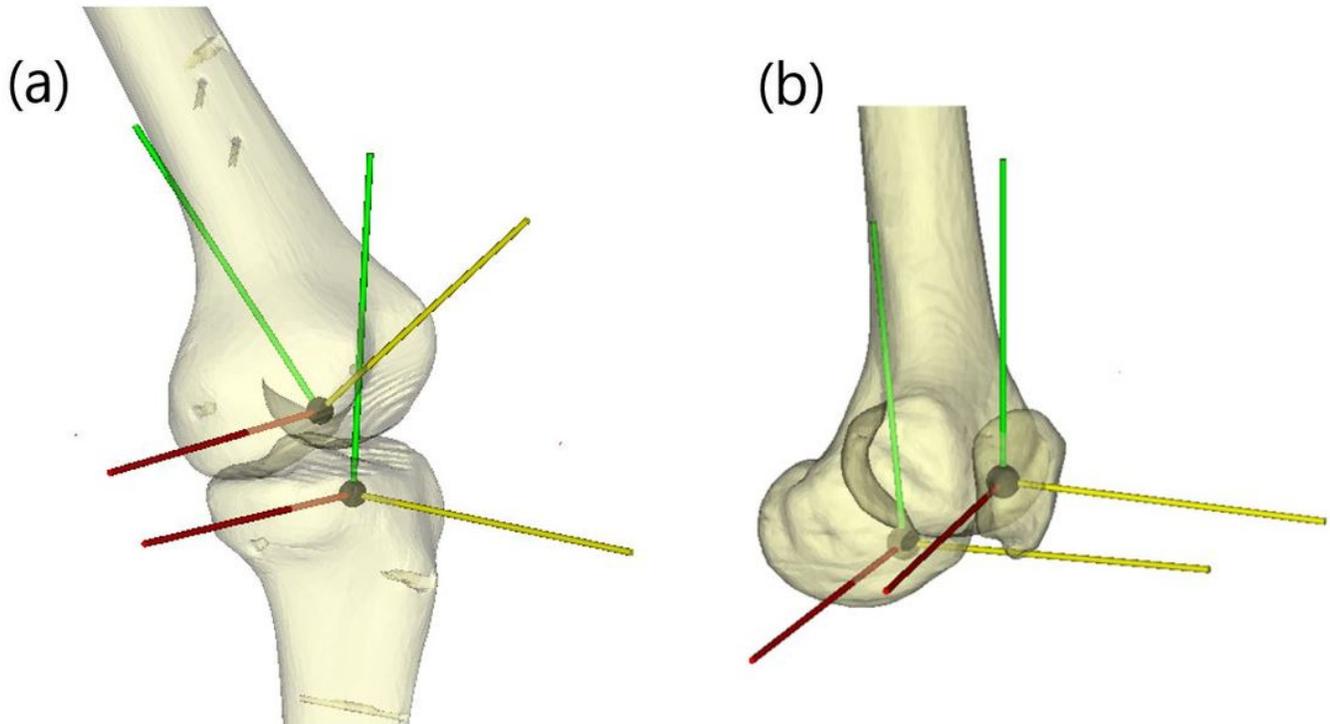


Figure 4

(a) Local coordinate systems of the femur and tibia, (b) local coordinate systems of the femur and patella.

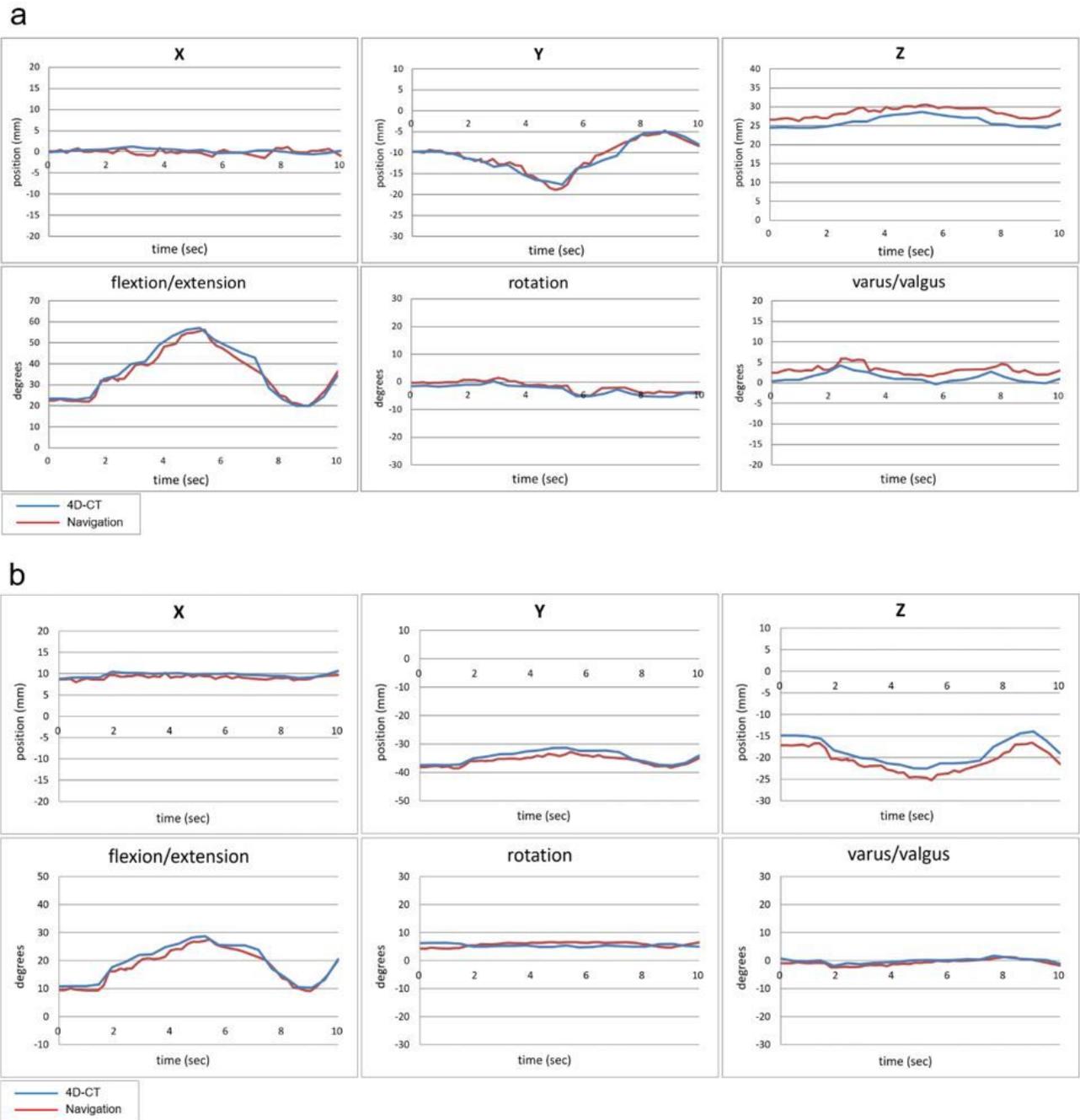
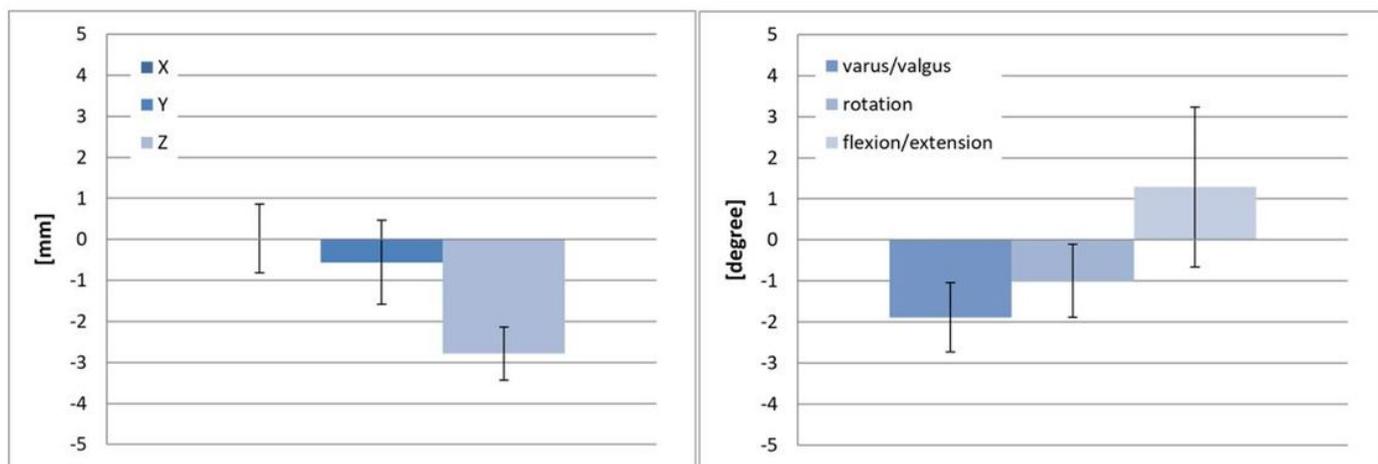


Figure 5

Changes in the position-posture measured by 4D-CT (blue line) and the navigation system (red line) in the FT joint (Fig 5-a) and the PF joint (Fig 5-b). 4D-CT and the navigation system showed similar movement patterns in both FT and PF joints.

a



b

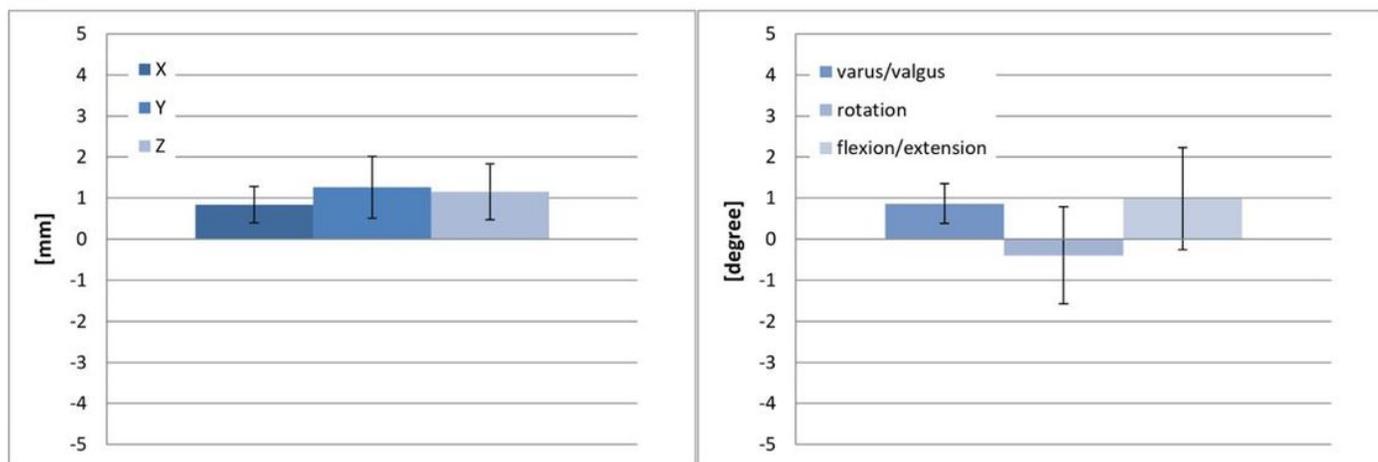


Figure 6

Differences between 4D-CT and the navigation system in the FT joint (a) and the PF joint (b). Differences are shown as relative values, indicating errors of up to 2.8 mm and 1.8° for the FT joint, and up to 1.3 mm and 1.8° for the PF joint. Thus, 4D-CT could measure the position and orientation with high accuracy.

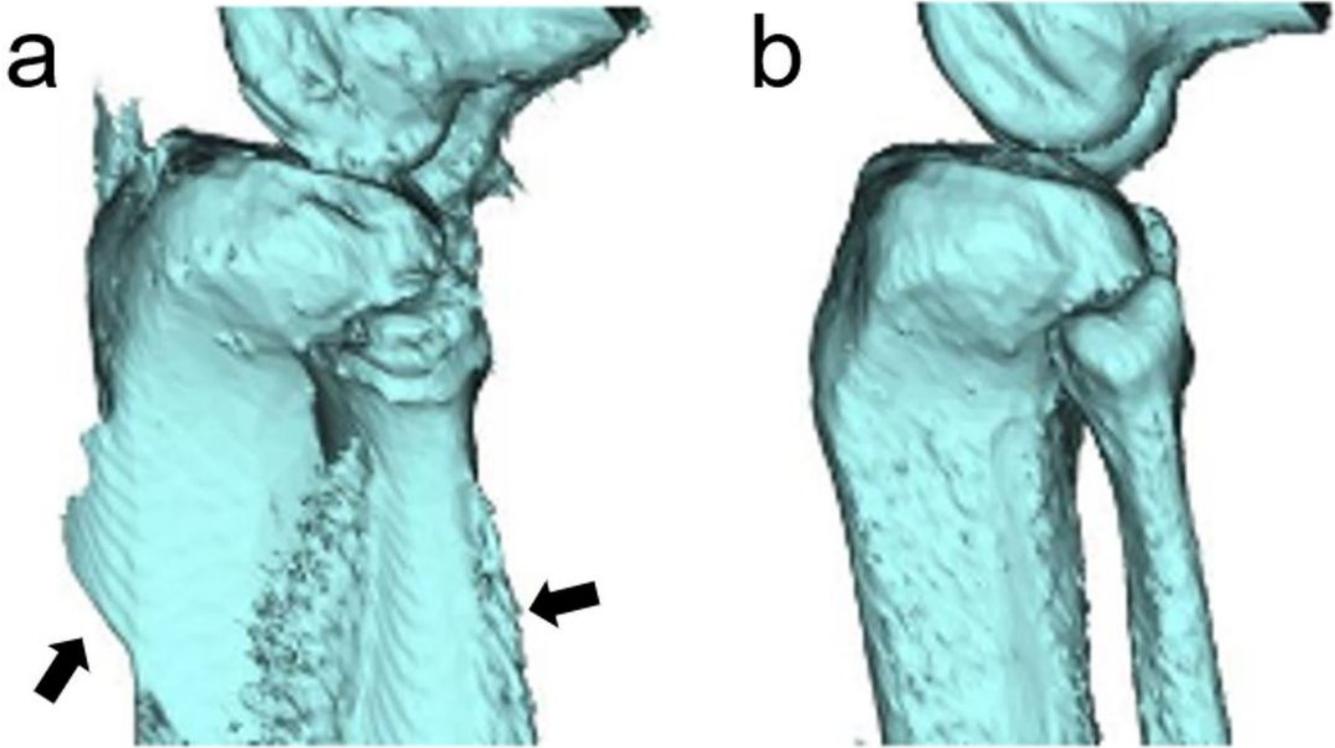


Figure 7

3D-CT model reconstructed from 4D-CT data. Some motion artifacts (arrows) occurred in the tibia and fibula during the mid-term flexion and extension movements (Fig. 7-a), where the movement speed was high. In contrast, when the movement speed was relatively low (that is, when the movement per unit time was small), no artifact was observed (Fig. 7-b).