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A Kinematic Assessment of Knee Prosthesis from Fluoroscopy Images

by

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Abstract

We have developed a technique for estimation 3D motion of knee prosthesis from its 2D perspective projections. Our estimation algorithm includes some innovations such as a two-step estimation algorithm, incorporative use of a geometric articulation model and a new method to solve two silhouettes' overlapping problem. Computer model simulations and experiments results demonstrated that our algorithms give sufficient accuracy. Next, with the cooperation of medical surgeons, we assessed the algorithm's clinical performance by applying it to moving fluoroscopy images of patients who had just undergone TKA recently. Our experiments were done in four steps; first we have taken the moving X-ray pictures called fluoroscopy images of the knee prosthesis at different knee motions; second, introduced the absolute positions/orientations for both components, third, introduced the relative positions/orientations between the femoral and the tibial components and finally, introduced the contact points trajectories between the femur and the tibial insert. We drew the estimation results graphically and made the CAD model pictures of the prosthesis, thereby helping us to assess how the relative motions between the femoral and the tibial components were generated. Estimation results of the clinical applications demonstrated that our algorithm worked well as like as theoretical.

Keywords: Knee prosthesis, Fluoroscopy images, Contact point trajectories, Kinematic estimation, Overlapping, Clinical applications.

1. Introduction

An increase in the demand for total knee arthroplasty (TKA) has necessitated improvement in the durability of TKA prostheses. *In-vivo* measurement of prosthetic kinematics can yield information vital for TKA prosthesis design. Since there is no practical method to measure directly prosthetic kinematics in-vivo, indirect techniques have to be applied.

Commonly used techniques produce 3D position/orientation estimations of prosthetic metal components from their projection in a 2D X-ray image[1)]. Banks and Hodge[2)] proposed a pattern matching method in which, the contours of pre-computed 2D images generated using a precise geometric model of a knee prosthesis in various poses are stored in a library. Zuffi et al.[3)]

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developed a method for measuring TKA kinematics, in which matching was performed by rotating/translating the computer model to minimize the Euclidean distance of the model surface from the projection rays drawn from the projection center to the detected contour of the prosthetic X ray images. Mahfouz et al.[4] measured the similarity between a direct X ray image and a registered computer model image, which they refer to as a 2D/3D registration technique.

The methods for measurement developed thus far still have weaknesses. To overcome the problems with the current techniques: to improve accuracy while minimizing computation time, we have developed some innovative algorithms. They are; i) A two-step estimation algorithm to accomplish accurate positions/orientations estimation for the prosthesis, ii) Incorporative use of a geometric articulation model, to improve estimation accuracy especially for the translation along the axis vertical to the image plane as well as to introduce contact point trajectories' between articulating surfaces, and iii) A new method to overcome the problem when the silhouettes of tibio and femoral components overlapped with each other.

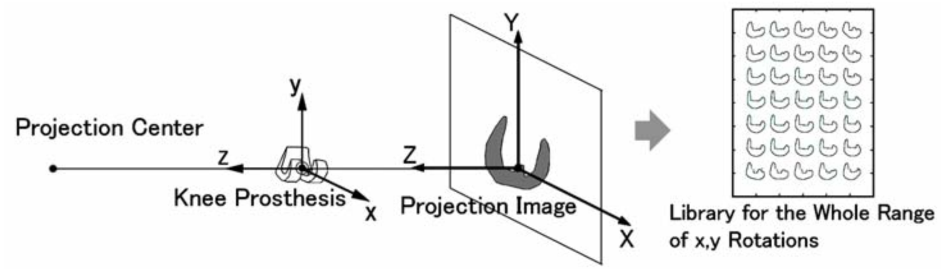
Next, with the cooperation of medical surgeons, we assessed the algorithm's clinical performance by applying it to moving fluoroscopy images of patients. Our experiment subjects were six patients who had just undergone TKA recently for their both legs. Knee Motions conditions were a) Passive flexion-extension while the patient was in the supine position, b) Joint passive flexion-extension and internal-external rotation while the patient was in the supine position, and c) A passive walking-like motion under partial weight while the patient was supported on both sides. We introduced estimation results not only the absolute positions/orientations but also relative positions/orientations between the femoral and the tibial components and contact point's trajectories between the femoral and the tibial insert. Since the knee was in the air during a) and b) the articulated surfaces may not have been in continuous contact, we did not incorporate the articulation model when making the estimations for a) and b). We drew the estimation results graphically and using these data we made CAD model pictures of the prosthesis. The CAD model from our estimation results was identical to the X-ray images. Then we could confirm our estimation results were correct. The aim of our study is, therefore, to validate our improved algorithm for the clinical assessment and to confirm our contribution in this field.

2. Algorithms

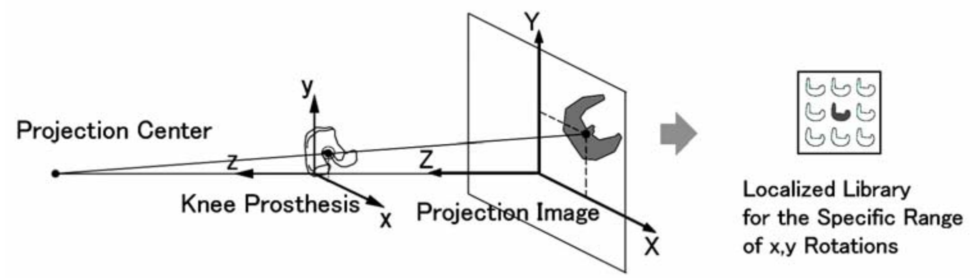
2.1 Theory

Two-step estimation algorithm

The coordinate conventions for perspective imaging are shown in **Fig. 1(a)** and **(b)** for the first-step estimation and the second-step estimation. The first step estimation was done; in the same way as banks and Hodge[2] on the assumption of orthogonal projection. In the second-step estimation, a computer-generated model was placed at the position/orientation introduced from the first-step estimation and its projection image was obtained. Then, rotations around x and y axes in small increments in both positive and negative directions were added to the model, thereby obtaining eight images surrounding the first image. A new image library was prepared, whose elements were the nine images as shown in **Fig. 1(b)**. Then we repeated the same process in the second-step estimation as the first-step estimation[5].



(a) First-step estimation.



(b) Second-step estimation.

Fig.1 The coordinate conventions and image libraries used in the first- and the second-step estimation processes.

Incorporation of the Articulation Model

One of the weaknesses the current methods have is that the estimation accuracy for the translation along the axis orthogonal to the image plane (depth translation) is poor compared with that for other rotations and translations. We incorporated a 3D geometric articulation model into the pattern matching algorithm to achieve substantial improvement of the estimation accuracy for the depth translation, and to introduce contact point trajectories between the femoral condyles and the tibial plateau (polyethylene insert) surfaces.

We created a 3D mathematical model representing the femoral and the tibial polyethylene insert as shown in **Fig. 2**. In the **Fig. 2**, the tibial polyethylene insert is described by a moving coordinate and the femoral component by a fixed coordinate. We introduce the z-translation value, solving the 3D mathematical articulation equations[5)], we obtained ten simultaneous equations; the number of unknown variables are fourteen. The unknown outnumber the equations by four. However; with respect to the tibio-femoral relative motions, six variables can be introduced from our pattern matching algorithm, reducing the number of unknown variables fourteen to eight. This gives two surplus equations, and we may recalculate two more variables as if they were unknowns.

Simulations and experiments using CCD pictures were performed to investigate the performance of our algorithm with respect to accuracy and computation time. We found that our algorithm produced position/orientation estimations that were more accurate that those of other methods, especially for depth translation at shorter computation time, and successively introduced contact point trajectories between the articulating surfaces.

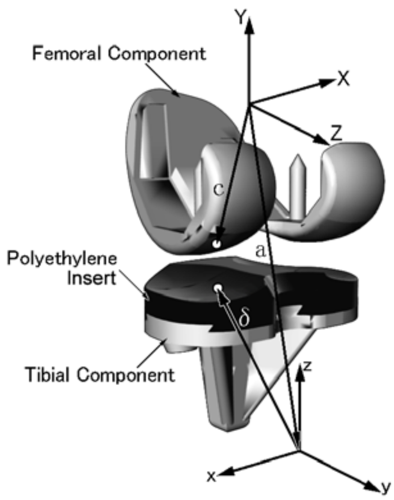


Fig.2 A 3-dimensional mathematical model of a femoral component and a polyethylene insert.

Countermeasure to the Overlapping between the Tibial and Femoral Silhouettes

As the entire silhouette contour of each prosthetic component was required, our algorithm did not function when the silhouettes of tibio and femoral components over-lapped with each other. To overcome the problem we planned a new method; which was processed in two steps. First, interpolate the missing parts of tibial and femoral contours due to overlapping with free-formed curvature such as Bezier as shown in **Fig. 3**, and the other is to use clipping windows in order for the missing parts to exclude from the estimation process.

We can easily identify the intersection from the curvature values because the contour forms an edge and the curvature becomes close to $-\infty$ at the intersections. When two intersections are identified along the contour, we will be able to distinguish the tibial and femoral silhouettes respectively from the overlapping silhouette.

We will restore the missing parts of silhouettes using Bezier curve interpolation as shown in **Fig 3**. Since the femoral condyle has a circular shape, the contour of its projection image usually forms an elliptical shape; which can be easily approximated by the Bezier curve. The control points at both ends of Bezier curve are assigned at the intersections. Surface of tibial tray in contact with a polyethylene insert has an irregular shape with grooves however; its silhouette contour shape is usually simple. Thus we will apply Bezier curve to the missing part of the femoral silhouette as well.

Since the original contour may not be reproduced exactly by means of Bezier interpolation, we will not be able to achieve highly accurate position/orientation estimation as expected. For this reasons, we will apply the Bezier interpolation technique only to the first-step estimation process.

In the next step as shown in **Fig. 4**, clipping window was set in the projective coordinate so as to separate the overlapped silhouette drawn using the first-step estimates. After that the localized library whose templates were clipped in shape was prepared and the second-step estimation was performed.

Fig.3 Interpolation by Bezier curvature to restore missing parts of silhouette due to overlapping.

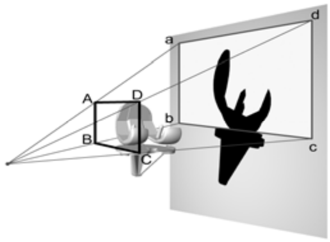
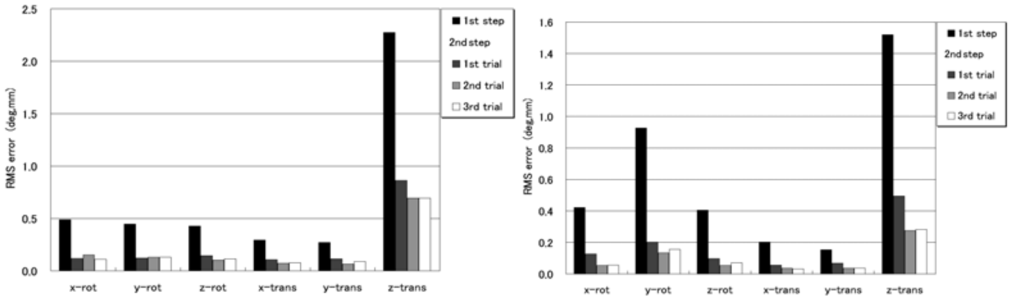


Fig.4 Projection through a clipping window.

2.2 Simulations and results

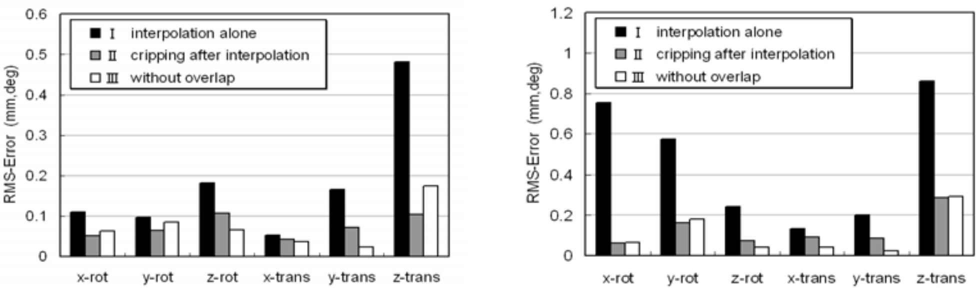
Simulations were conducted to assess the accuracy of our two-step estimation algorithm. The rotation and translation conditions applied to the computer model to create the library needed for the first-step estimation and the second step-estimation. The rotation about z-axis and all other translations were set at zero. The angles were set over a range of -12^{o} to 12^{o} about the x-axis and -24^{o} to 24^{o} about the y-axis. The elements interval for the x-and y- rotation in the library was set at 2^{o} for the first-step estimation and was set at 2^{o}, 1^{o} and 0.5^{o} for the second-step estimation at first-, second- and third-trial.



(a) femoral component (b) tibial component

Fig.5 Decrease in errors according to the estimation process.

Figure 5(a) and **(b)** show the comparative simulation results of the first-step estimation and the second-step estimation. The values of vertical axes for each graph are the root mean square (RMS) of estimation errors. Rapid decreases in errors between the first-step estimation and second-step estimation are marked as shown in the figures. Thus it is mentionable that our method (second-step estimation) worked reasonably well as compared to the Banks and Hodges[2)] method (first-step estimation). We found that the accuracies were much improved after the second-step estimation was processed despite that the total number of library elements was decreased.



(a) femoral component (b) tibial component

Fig.6 Simulation results of the overlapping.

For the overlapping method, **Fig. 6(a)** and **(b)** show the simulation results for the femoral and tibial components respectively. The Computer model simulations demonstrated that corporative use of the Bezier interpolation and the clipping process in accordance with two-step estimations could achieve estimation accuracy as high as those of the images without overlapping.

3. Clinical Applications

3.1 Materials and methods

3.1.1 Experiment process

Clinical applications of the algorithm were done at Katai Hospital (Fukuoka, Japan). Total subjects of our experiment were six patients. The patients who participated in the experiment were newly surgery patients; all were female and average age was 60 years. They were suffering rheumatoid arthritis. They were bearing knee prostheses for their both knees. The right knee was participating to the experiment and the other knee was rest and vise-versa. The prosthesis knees were NRG type (Stryker Co. USA) with different sizes for both the femoral component and the tibial component. The moving x-ray pictures, namely fluoroscopic images of the prosthetic motion were recorded using the X-ray video recorder (MCA-501, Medison Acoma Co., USA). The experimental environment is shown in **Fig. 7**

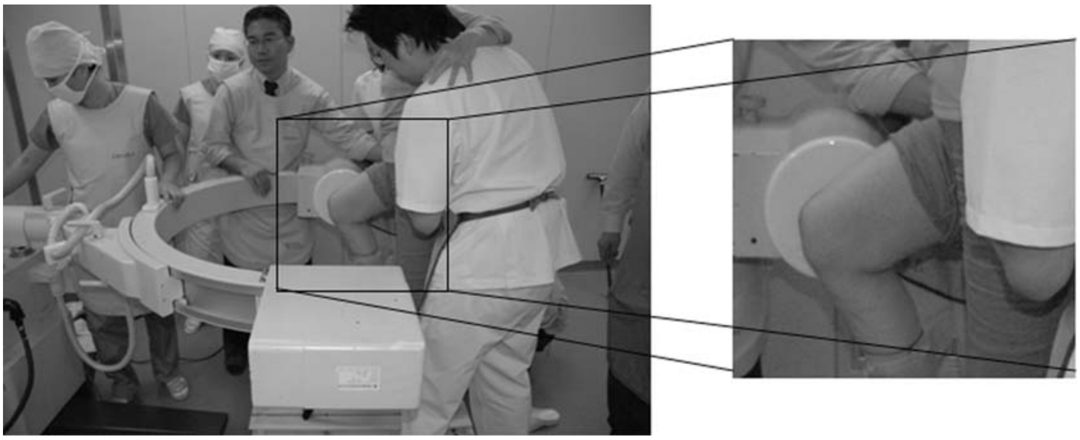


Fig.7 Experimental environment for Clinical Assessment.

The following three kinds of knee motions were chosen for the measurement,

a) Knee flexion-extension

The prosthetic patient had been taken the position on the bed in a laying supine posture and the right knee had been done flexion as possible as maximum of her reasonable limit. We started the experiment with the limit of flexion with her knee. Then the prosthesis knee had done straight i.e. parallel to the body of her knee very slowly. After reached the straight position again come back the first position of her knee i.e. flexed as possible as the maximum limit of the patient capacity and vise- versa and completed the one cycle. We repeated the same work four times. And we obtained the moving X-ray pictures of the knee prosthesis.

b) Knee flexion-extension and internal-external rotation

The experiment was done with two works jointly; one was flexion-extension and the other was internal-external rotation. All the motions were done passively.

The experiment started with knee angle at 120°, the knee angle was gradually decreased and fixed at 90°, 60°, 30° and up to 0° respectively. At each flexion angle, the knee was internally rotated as possible as the maximum limit of the patient capacity and then externally rotated in the same way.

c) Walking-like motion supported on both sides

In this condition, the patient's body weight partially passed through the prosthetic knee. The patient put her foot of the subjective limb on the table. The patient being supported on both sides; changed her knee positions from the half portion of the stand up to the half portion of the sit-down and vise-versa; this completed one full cycle. We repeated the same works two times. And we took the moving X-ray pictures of the prosthetic motion for a full cycle.

3.1.2 Analysis process

After taking moving X-ray pictures for each experiment, we introduced the absolute positions/orientations for each component, the relative positions/orientations between the femoral and the tibial components, and the contact point's trajectories between the femur and the tibial insert as shown in **Fig. 8**.

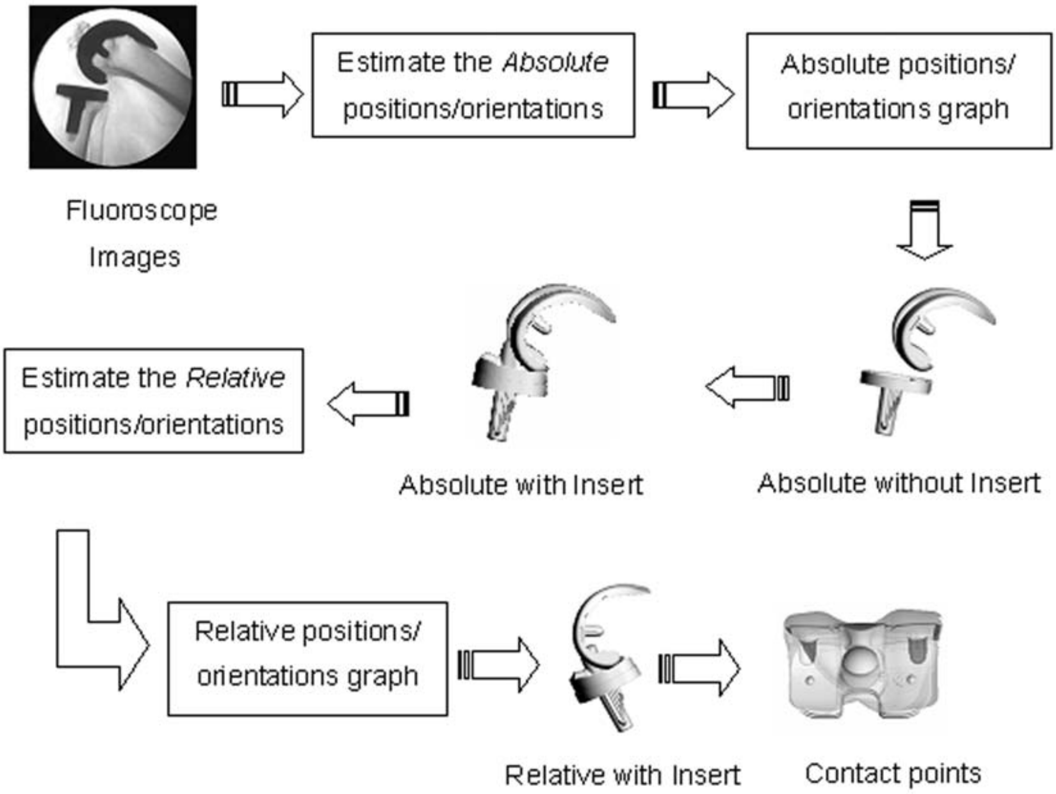


Fig.8 Flowchart showing steps in the analysis process.

In the first step of the analysis process, we captured the x-ray pictures frame by frame from the moving x-ray pictures. Since the knee motion was not generated with constant speed, the amount of displacement for each rotation or translation was not equal between the same time intervals. Thus we skipped to capture the frames if the knee did not move much, and captured the frames depending on the amount of rotations or translations. Then using our pattern matching algorithm[5)], we estimated the absolute rotations/translations for each component for each experimental condition and represented the results graphically. Further we illustrated the CAD model pictures of the prosthesis with the estimated position/orientation so that we could compare them with the captured X-ray pictures frame by frame.

In the second step, we calculated the values of relative position/orientation between the femoral and the tibial components and represented the results graphically. In this step, depending on which component moved much as compared to the other, either of the femur or the tibia was settled on the neutral position/orientation and the relative position/orientation of the other component to the settled component were introduced. Further we illustrated the pictures of the CAD model of the prosthesis under the condition that either the femur or the tibia was standstill, thereby helping us to understand how the relative motions between the femoral and the tibial components were generated. Finally, using the equations and processes described in our preceding paper[5)], we introduced the contact points' trajectories between the articulating surfaces, and made illustrations of them.

3.2 Results

a) Knee flexion-extension: The analysis of the fluoroscopic moving images for the knee flexion-extension was performed according the above-mentioned analysis process. **Figure 9** shows the x-ray pictures captured from the fluoroscopic images at knee flexion-extension. The graphs of the absolute position/orientation estimates for the components demonstrated that the z-rotation of tibia varied much, while all other kinds of rotations did little in both the components. Since the tibial component moved much relative to the femoral component, the relative rotations/translations were introduced with the femoral component fixed. **Figure 10** shows the relative rotations of the tibial components to the femoral components. Since the knee was in the air during the knee motion, the articulation was not maintained and therefore we could not introduce the contact point's trajectory.

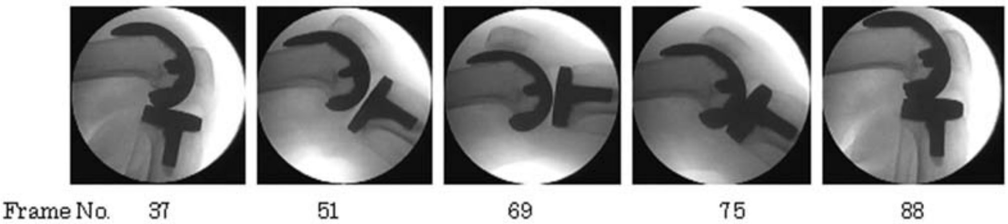


Fig.9 Still pictures captured from the fluoroscopy.

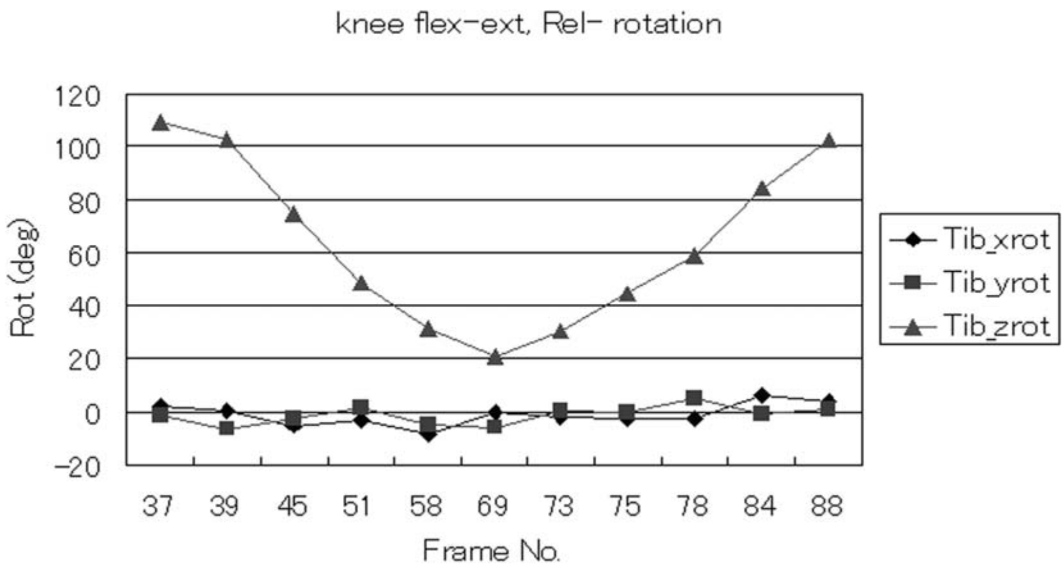
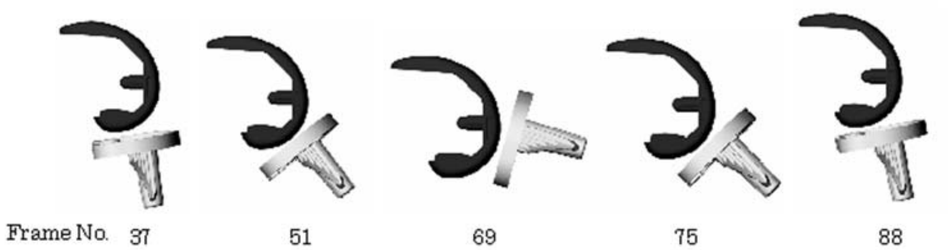


Fig.10 Variation of the tibial rotation to the femur during knee flexion-extension.



(a) Without the insert.

(b) With the insert.

Fig.11 CAD model representations of the tibial rotations/translations relative to the femur.

Figure 11(a) and **(b)** show examples of the results introduced from CAD model representation of the tibial rotations and translations relative to the femur without insert and with insert. Because of space limits, only 5 images are shown. The contour shape of each CAD model in **Fig. 11(a)** is close to that of **Fig. 9**, which confirms that the estimation was processed properly.

b) Knee flexion-extension and internal-external rotation: Figure 12 shows still images captured from the fluoroscopy (upper) and the middle three and lower three are the CAD model pictures viewed from two different directions at 90° of knee flexion respectively with the maximum internal, neutral and the maximum external rotations while the patient was lying supine. Using the method[5], we were able to estimate the position/orientation for each component even in the overlapping silhouettes, such as picture number 43 and 48 in **Fig. 10**. In this motion the movement of z-rotation is same as the condition of knee flexion-extension, i.e. the z-rotation of the tibial component moved much while that of the femoral component little.

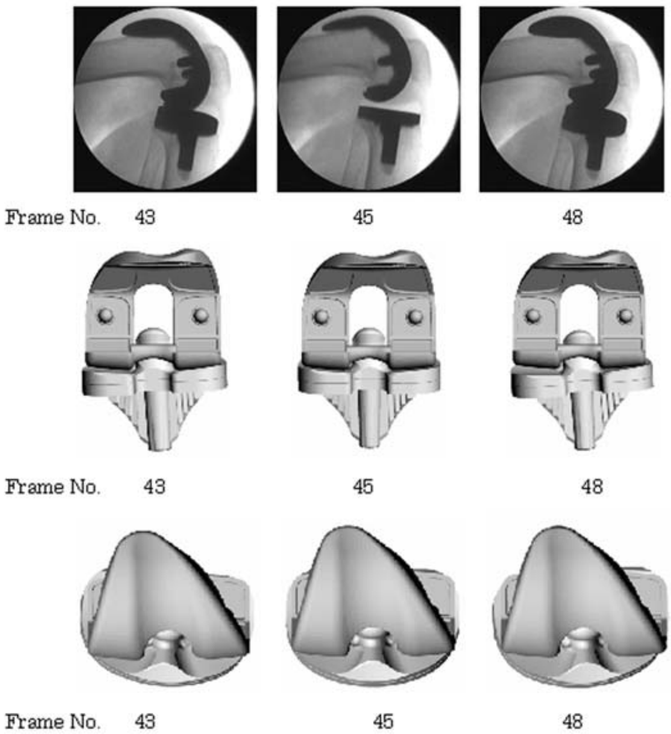
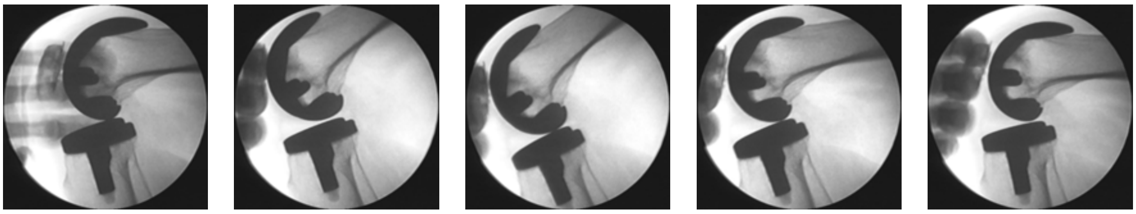


Fig.12 The results from knee flexion-extension and internal-external rotation at 90° of knee flexion, the upper three are still pictures captured from the fluoroscopy; the middle three are in posterior views of the CAD models and the lower three are the horizontal views of the CAD models representations of the tibial rotations/translations relative to the femur.

Since the tibial component moved much, the relative rotations/translations were introduced with the femoral component fixed. Once we obtained the relative position/orientation data, we were able to make CAD model pictures viewed from the desired direction. Since the internal-external rotation accompanied the valgus-varus motion, we made the CAD model pictures viewed from the posterior side as the middle three pictures and the horizontal views as the lower three pictures as shown in **Fig. 12**. The CAD models demonstrate that at 90° of knee flexion, the femoral component and the tibial insert lift off each other on the lateral side.

c) Walking-like motion supported on both sides: Figure 13(a) and **(b)** show examples of the results from walking-like motion. In the **Fig. 13(a)** shows a series of still images captured from the fluoroscopy at nearly equal intervals of angular displacement of knee flexion. In this condition rotation especially z-rotation of the femur changes much between any two frames but that of the tibial component changes little. So, we introduced the relative rotations/translations of the femoral components to the tibial components. **Figure 13(b)** shows the contact points between the articulating surfaces. Since the patient was supported on both sides, she did not put her total body weight on her prosthetic knee. Still it was possible to introduce the contact points. From **Fig. 13(b)**, we know that the contact points on either the femoral condyle or the insert do not move much.



Frame No. 412 417 425 432 442

(a) Still pictures captured from the fluoroscopy.

Frame No. 412 417 425 432 442

(b) Contact points' locations between the femur and the tibial insert.

Fig.13 Examples of the results from walking-like motion.

4. Discussion

As the several methods produce 3D positions/orientations of the objects from their projections, these methods are applicable only for visible objects; take the pictures any desire (two or more) directions of the objects. Some methods also need sensors. But these methods are not practical method to measure prosthetic kinematics in-vivo. Knee prostheses are inside of the human body and only their silhouettes contours of the prosthetic knee are visible in an x-ray. We also know that the radiation of x-ray is harmful for the body and we can not take the X-ray pictures from many directions. Our pattern matching method takes the x-ray from only one direction. Under these special conditions, our pattern matching method is the best method to estimate the 3D positions/orientations of prosthetic knee in-vivo. Our pattern matching method gives the sufficient accuracies to estimate 3D positions/orientations from the x-ray of prosthetic knee.

The features of our two-step estimation algorithm which could achieve suitable and consistent algorithm for the relative motion estimation and the second-step estimation could decreased the estimation errors by one fifth introduced from the first-step estimation. To incorporate the 3D mathematical model of articulation between the femoral condyles and the polyethylene insert into the pattern matching algorithm, not only made it possible to introduce the contact point trajectories but also helped us to achieve improvement of estimation accuracies especially for z-translation. For countermeasure to the overlapping between the tibial and femoral silhouettes, corporative use of the Bezier interpolation and the clipping process in accordance with two step estimations could achieve estimation accuracy as high as those of the images without overlapping.

Clinical application results demonstrate that our algorithms are reasonable well as like as theoretical even though we applied on the different kinds knee motions. Making the information of TKA kinematics, we have analyzed different way: first represent the absolute positions/orientations of TKA graphically and then using numerical data we have created CAD model animations and analyzed from different views/directions. Second, we have represented the relative positions/orientation graphically and using those data we have created CAD model animations. CAD model animation is quite helpful to assess knee kinematics visually because we can analyze any direction and rotation of the knee. Since we analyzed in the CAD animation not only absolute positions/orientations but also relative positions/orientations and we found that our estimates are identical to the fluoroscopy images. So, we could confirm estimation was correct. Some times results have given us large errors of z-translation results in the second step estimation especially for the tibial component. In this case, to solve the z-translation errors, we incorporated the 3D mathematical model of articulation between the femoral condyles and the polyethylene insert into pattern matching algorithm.

Our limitation is our experiment subjects were six only and knee motions under limited conditions in TKA patients. We will continue the experiments on different subjects with different knee motions, thereby providing useful information to the clinicians.

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