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2-D/3-D Image Registration of Implanted Knee DR Images with Kalman Filter

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***Abstract*— Total knee arthroplasty (TKA) is an orthopedic surgery which replaces the damaged knee joint with the artificial one. To diagnose the function of the implanted knee joint, it is effective to estimate 3-D knee kinematics in vivo. There are some conventional methods for estimating kinematics of the implanted knee using 2-D/3-D image registration for X-ray fluoroscopic images and 3-D geometrical models of the knee implant. However, these methods are based on static image analysis although the knee joint continuously moves. This paper proposes an analysis method of the knee kinematics using digital radiography images with Kalman filter. Use of Kalman filter enables us to take into account the continuous knee movement. The experimental results showed that the proposed method estimated the knee joint angles within a mean error of 0.31 deg.**

***Keywords*—Kalman Filter, Kalman Smoothing, Total Knee Arthroplasty, 2-D/3-D Image Registration**

I. INTRODUCTION

Total knee arthroplasty (TKA) is an operation which replaces the damaged knee joint with the artificial knee implant. The knee implant mainly consists of femoral component, tibial component and tibial insert. However, a functional movement of the implanted knee *in vivo* is still not well understand. In addition, it is important to evaluate the implanted knee kinematics in order to diagnose the TKA patients and to evaluate TKA operation method and design of TKA implants. Therefore, an analysis of the implanted knee kinematics has been attracting the considerable attention in the field of orthopaedic field.

Some studies has proposed methods for estimating 3-D kinematics of the implanted knee based on 2-D/3-D image registration in X-ray radiograph, X-ray fluoroscopy, or digital radiography (DR) images [1][2][3][4]. Their methods define a similarity index between the evaluating 2-D image and a candidate 3-D pose/position of 3-D geometric model of the knee implant. And, a pose/position parameter with the highest similarity index is searched by using heuristic parameter optimization techniques such as simulated annealing (SA) [5]. And, the knee joint angles; flexion/extension (f/e) angle, internal/external (i/e) angle, and varus/valgus (v/v) angle are quantified according to Grood coordinate system [6].

Most heuristic parameter optimization techniques require an initial parameter. It is very important to select appropriate initial parameter because parameter optimization in the higher-dimensional parameter space (six degree-of-freedom in this study) often falls into local maxima, and the estimation accuracy strongly depends on the initial parameter. Most conventional approaches use the estimated parameter at the previous frame as the initial parameter. The other methods are estimate the initial parameter by a liner prediction. The principal problems of their approaches are that the estimation result varies between adjacent frames, and estimation error is accumulated. In addition, the estimated movement/rotation of the knee implant becomes discontinuous because the conventional methods do not consider continuous movement of knee kinematics, and the estimation result obtained in a frame does not continue to the next frame. Thus, it is necessary to estimate a 3-D pose/position with a continuous movement of the knee implant.

This paper proposes a knee kinematics analysis system with 2-D/3-D image matching and Kalman filter using DR image and 3-D geometric models of the knee implant. By introducing Kalman filter to estimate initial parameters, we improve estimation accuracy. The proposed method is validated by using computer-synthesized images.

II. PRELIMINARIES

A. TKA Impants and Digital Radiography image

The knee implant mainly consists of femoral component, tibial component and tibial insert as illustrated in Figure 1. The tibial component is implanted to the tibia, the femoral component is implanted to the femur, and the tibial insert is inserted between the components as a substitute of the cartilage. The femoral and the tibial components are made from metal. The X-ray transmissivity is extremely low, and the components are depicted by black in DR images. In addition, the tibial insert is depicted by similar intensity to soft tissues because the tibial insert is made from polyethylene whose X-ray transmissivity is high. The 3-D geometric model of the TKA implants is provided by stereolithography (STL) format.

This study used a 2-D DR image of the knee joint. The image acquisition parameters were a spatial resolution of 1024 × 768 pixels, a field of view of 400 mm × 300 mm, a frame frequency of 60 fps. X-ray was projected perpendicularly to the center of X-ray intensifier, and the distance between the X-

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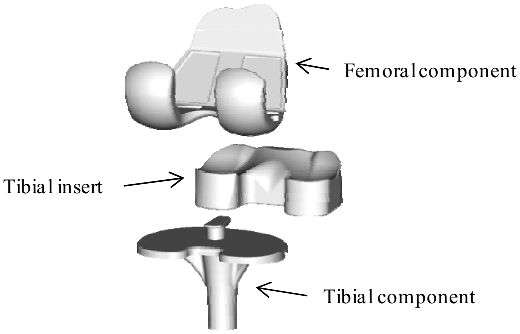


Figure 1. 3-D knee implant model.

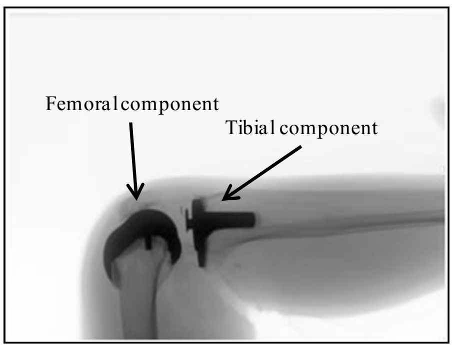


Figure 2. Example of DR image.

ray source and the intensifier was 1200 mm. For each subject, 300 frames were taken during 5 sec. An example of DR image is shown in Figure 2. As shown in this figure, the femoral component and the tibial component are depicted by the lower intensity than the neighboring soft tissues.

The coordinate system used in this study is a right-handed *x-y-z* coordinate system where the origin is the left corner of DR image, the horizontal axis is *x-axis*, the vertical axis is *y-axis*, and z-axis is the cross product of *x-axis* and *y-axis*.

B. Kalman Filter and Kalman smoothing

Kalman filter is a method to estimate a state from chronological order information [7][8]. The system model of the Kalman filter is expressed by a state equation (1) and an observation equation (2).

$$x_{k+1} = F_k x_k + G_k u_k + w_k \text{ and} \tag{1}$$

$$y_k = H_k x_k + v_k, \tag{2}$$

where x_k and y_k are a state quantity and an observation quantity of the system, respectively, u_k is a movement vector, w_k is a state noise, and v_k is an observation noise at time *k*. F_k, G_k and H_k are parameters of the system. The Kalman filter predicts a current state from a state at time *t-1* and updates the state from real observation value as follows.

$$\hat{x}_{k|k-1} = F_k \hat{x}_{k-1|k-1} + G_k u_k, \tag{3}$$

$$\hat{P}_{k|k-1} = F_k \hat{P}_{k-1|k-1} F_k^T + G_k Q_k G_k^T, \tag{4}$$

$$K_k = \hat{P}_{k|k-1} H_k^T \left[H_k \hat{P}_{k|k-1} H_k^T + R_k \right]^{-1}, \tag{5}$$

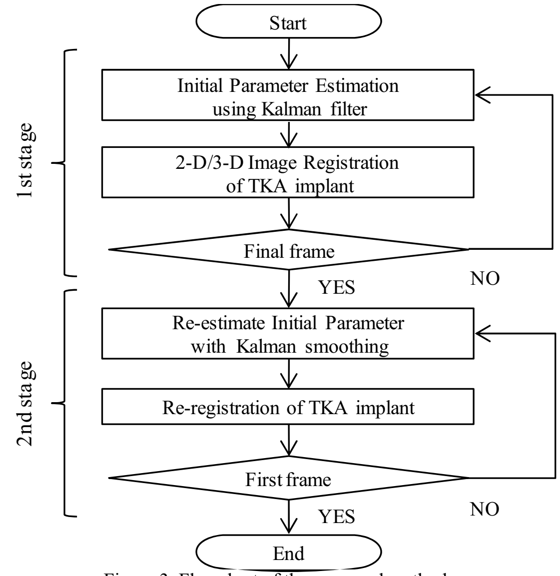


Figure 3. Flowchart of the proposed method.

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k (z_k - H_k \hat{x}_{k|k-1}) \text{ and} \tag{6}$$

$$\hat{P}_{k|k} = \hat{P}_{k|k-1} - K_k H_k \hat{P}_{k|k-1}, \tag{7}$$

where $\hat{x}_{k|k-1}$ means a state prediction from a state at time *t-1*, and $\hat{P}_{k|k-1}$ is an error covariance matrix which is estimated by a state at time *t-1*. $\hat{x}_{k|k}$ is an update value and $\hat{P}_{k|k}$ is an update error covariance matrix.

Kalman smoothing is a method that calculates a current smooth estimation from a past and a future states. The Kalman smoothing algorism calculates a smooth value based on a state that is estimated with the Kalman filter:

$$C_{t-1} = \hat{P}_{t-1|t-1} F_t^T \hat{P}_{t|t-1}^{-1}, \tag{8}$$

$$\hat{x}_{t-1|N} = \hat{x}_{t-1|t-1} + C_{t-1}(\hat{x}_{t|N} - \hat{x}_{t|t-1}) \text{ and} \tag{9}$$

$$\hat{P}_{t-1|N} = \hat{P}_{t-1|t-1} + C_{t-1}(\hat{P}_{t|N} - \hat{P}_{t|t-1}) C_{t-1}^T, \tag{10}$$

where $\hat{x}_{t-1|N}$ is a smooth value and $\hat{P}_{t-1|N}$ is a smooth error covariance matrix. *N* is a section of smoothing and shows a number of analysis frames.

III. PROPOSED METHOD

A. Overview

3-D kinematics of the implanted knee is estimated by estimating 3-D pose/position of the TKA implant using 2-D/3-D image registration of DR images and 3-D geometric models of the TKA implant. The proposed method consists of two stages. Firstly, for each frame in ascending order, 3-D pose/position of TKA implant is estimated by applying 2-D/3-D image registration whose initial parameter is estimated by using Kalman filter. Secondly, for each frame in descending order, initial parameter is estimated by using Kalman smoothing, and 3-D pose/position of TKA implant is re-estimated by using the estimated initial parameter. The flowchart of the proposed method is shown in Figure 3, and is applied to each of the femoral and the tibial components.

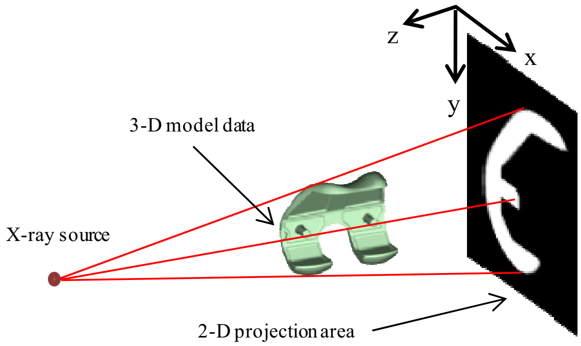


Figure 4. Computer synthesizing of DR images.

B. 2-D/3-D Image Registration of TKA implant

3-D pose/position of the knee implant at frame t is expressed by a parameter set,

$$\mathbf{P}(t)=\left[t_x(t),t_y(t),t_z(t),\theta_x(t),\theta_y(t),\theta_z(t)\right]^T, \qquad (11)$$

where $t_x(t)$, $t_y(t)$ and $t_z(t)$ are translation parameters at frame t, and $\theta_x(t)$, $\theta_y(t)$, and $\theta_z(t)$ are rotation angles for each axis at frame t. Using the parameter set, a silhouette image of TKA implant is synthesized by a perspective projection using the DR imaging parameters, as shown in Figure 4. Similarity index between the computer-synthesized silhouette image and DR images is defined by the following equations.

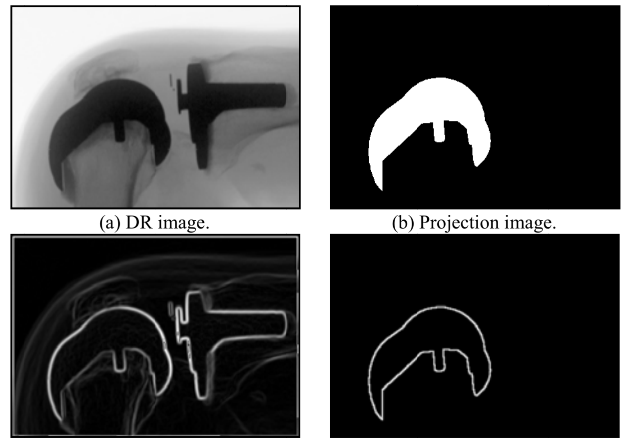
$$S=\omega S_I+(1-\omega)S_D, \qquad (12)$$

$$S_I=\frac{\sum G(x,y)H(x,y)-\sum G(x,y)\sum H(x,y)/p}{\sqrt{\sum G(x,y)^2-(\sum G(x,y))^2/p}\sqrt{\sum H(x,y)^2-(\sum H(x,y))^2/p}} \qquad (13)$$

and

$$S_D=\frac{\sum J(x,y)K(x,y)-\sum J(x,y)\sum K(x,y)/p}{\sqrt{\sum J(x,y)^2-(\sum J(x,y))^2/p}\sqrt{\sum K(x,y)^2-(\sum K(x,y))^2/p}}, \qquad (14)$$

where S is the similarity index, ω is a weight parameter, $G(x,y)$ and $H(x,y)$ are pixel values of DR image (Figure 5(a)) and the synthesized silhouette image (Figure 5(b)), respectively. $J(x,y)$ and $K(x,y)$ are pixel values of the differential images of DR image (Figure 5(c)) and the synthesized silhouette image (Figure 5(d)),



(a) DR image. (b) Projection image.

(c) Differential image of DR image. (d) Differential image of projection image.

Figure 5. Calculation of similarity index.

Optimal parameter set is searched by using SA technique. For the first frame of DR images, the initial parameter set is manually given by the user. After that the initial parameter set is estimated by Kalman filter at the first stage and estimated by Kalman smoothing at the second stage.

C. Initial Parameter Estimation using Kalman filter

After finding the optimal parameter set using SA at frame t, the parameter set at frame t is updated by using Kalman filter. Because the proposed method predicts the parameter set at frame t from the parameter set at the frame t-1 by liner prediction, parameters of Kalman filter F and G are set to 1. Thus, the state equation (3) is rewritten into:

$$\hat{\mathbf{P}}(t)=\hat{\mathbf{P}}(t-1)+u(t-1), \qquad (15)$$

where $\hat{\mathbf{P}}(t)$ is the predicted parameter set at frame t, and $u(t-1)$ is calculated by:

$$u(t-1)=\hat{\mathbf{P}}(t-1)-\hat{\mathbf{P}}(t-2). \qquad (16)$$

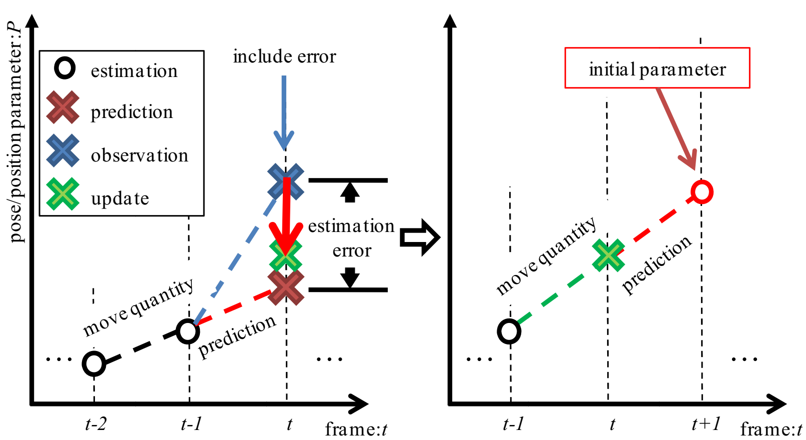


Figure 6. Prediction and update with Kalman filter.

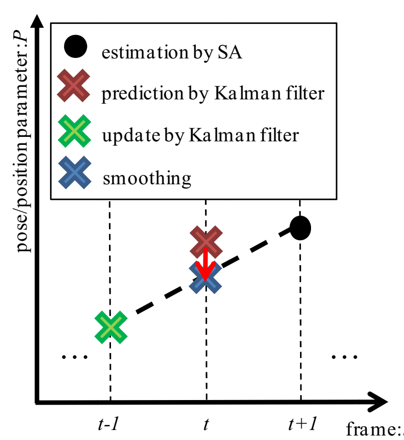
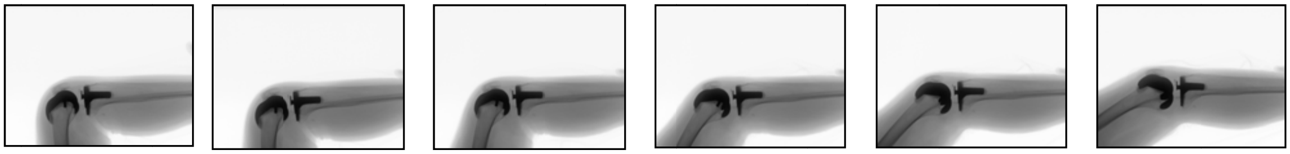
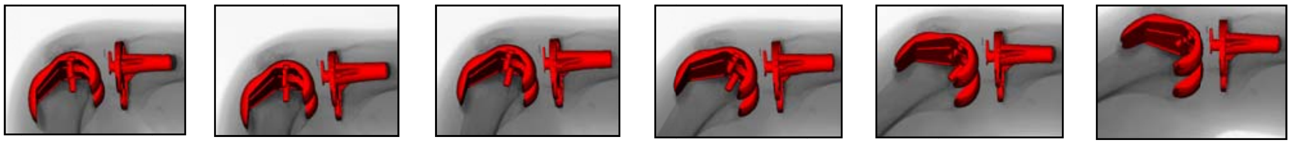


Figure 7. Kalman smoothing.



(a) 1/300 frame. (b) 100/300 frame. (c) 150/300 frame. (d) 200/300 frame. (e) 250/300 frame. (f) 300/300 frame.

Figure 8. DR images for patient after TKA.



(a) 1/300 frame. (b) 100/300 frame. (c) 150/300 frame. (d) 200/300 frame. (e) 250/300 frame. (f) 300/300 frame.

Figure 9. Estimation results with the proposed method.

And, the observation parameter set at frame t is given by the parameter set obtained by using SA at frame t. Thus, according to Equation (6), the parameter set at frame t is updated by:

$$\hat{Q}(t) = \hat{P}(t) + K(t)\Big(P(t) - \hat{P}(t)\Big), \tag{17}$$

where $\hat{Q}(t)$ is the updated parameter set at frame t by Kalman filter. The initial parameter set at frame $t+1$ is estimated by linear prediction using the updated parameter sets at frame t and frame t-1. The mechanism of estimating initial parameter set at frame $t+1$ is illustrated in Figure 6.

D. Re-estimate Initial Parameter with Kalman smoothing

After estimating parameter sets from all frames, the proposed method proceeds to the second stage. The second stage re-estimates the initial parameter sets by using Kalman smoothing. According to Equation (9), the new initial parameter set at frame t is smoothed by:

$$\hat{R}(t) = \hat{P}(t) + C(t)\Big(\hat{R}(t+1) - \hat{P}(t-1)\Big)C^{T}(t), \tag{18}$$

where $\hat{R}(t)$ is the new initial parameter set at frame t estimated by using Kalman smoothing, $\hat{P}(t)$ is the predicted parameter by Kalman filter, and $\hat{C}(t)$ is the coefficient of Kalman smoothing. The coefficient set at frame t is demanded on the covariance set at frame t by using Kalman filter.

Using the new initial parameter set, the optimal parameter set at frame t is searched by using SA technique. In summary, as shown Figure 7, the new initial parameter is smoothed using

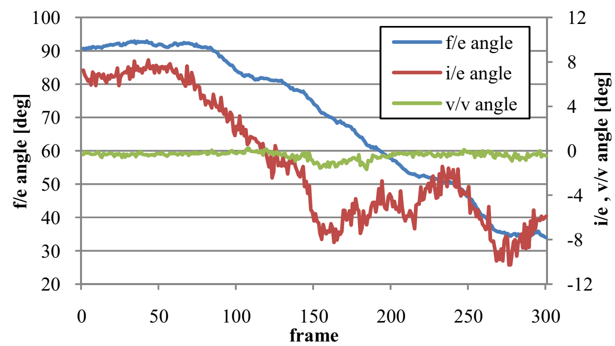
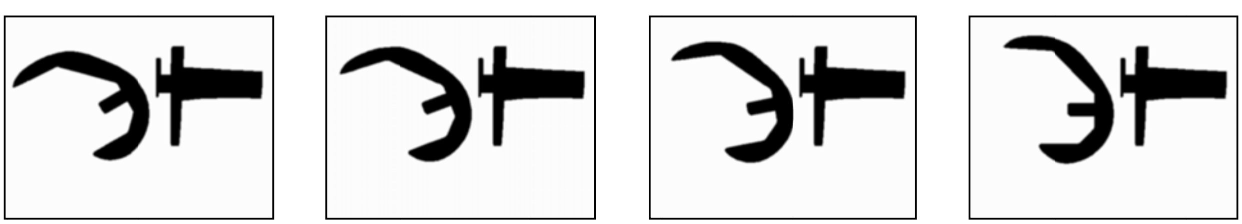


Figure 10. Estimated knee joint angles.

the predicted parameter set at frame t, the updated parameter set at frame t-1 by using Kalman filter and the optimal parameter set at frame $t+1$ obtained by using SA.

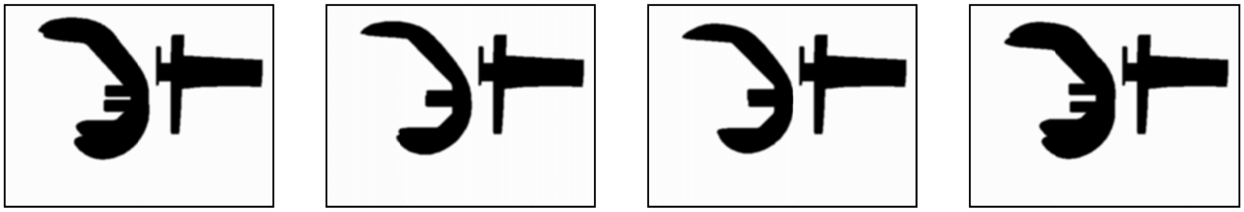
IV. Experimental Results

The proposed method was applied to DR images of TKA patient (female, right knee was operated). During image acquisition, the subject extended the implanted knee with the supported active movement. Figure 8 shows the DR images, and Figure 9 shows estimation results with the proposed method in which 3-D geometrical models of TKA implant were rendered and superimposed on the raw DR images. Figure 10 shows the estimated knee joint angles. This figure shows that the tibial component was internally rotated by extending the knee joint. As shown in these results, the proposed method estimated appropriate pose/position of the knee implant *in vivo*, and estimated the knee joint angles.



(a) 1/31 frame. (b) 10/31 frame. (c) 20/31 frame. (d) 31/31frame.

Figure 11. Computer-synthesized image with flexion (data 1).



(a) 1/31 frame. (b) 10/31 frame. (c) 20/31 frame. (d) 31/31frame.

Figure 12. Computer-synthesized image with external rotation (data 2).

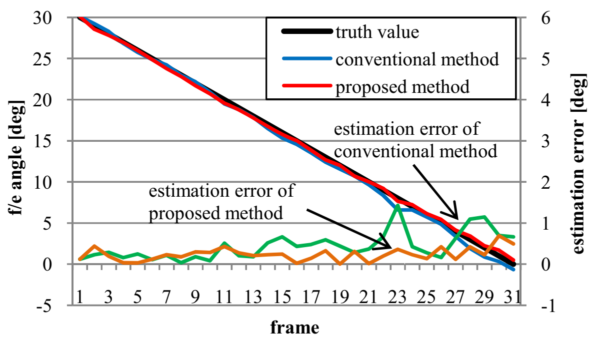


Figure 13. Estimated flexion angle for data 1.

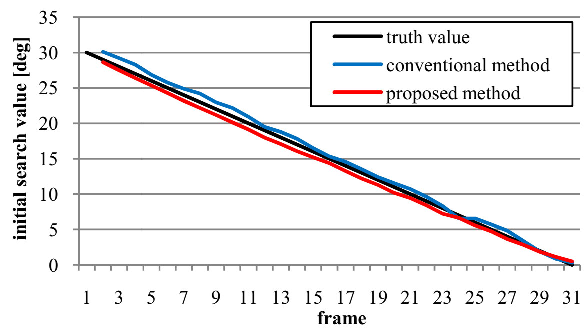


Figure 15. Initial flexion angle for data 1.

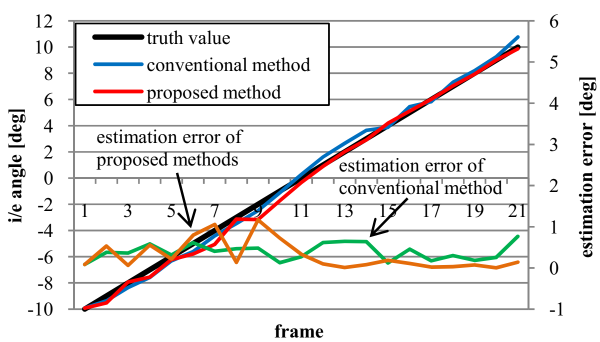


Figure 14. Estimated internal/external rotation angle for data 2.

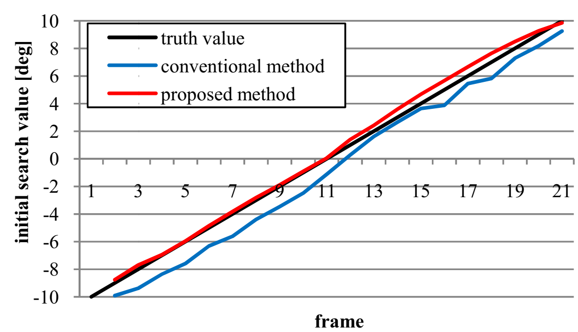


Figure 16. Initial internal/external rotation angle for data 2.

To evaluate the accuracy of estimating knee joint angles, the proposed method was applied to computer-synthesized DR images in which the tibial component was fixed and the femoral component was rotated for flexion direction (data 1) or external rotation direction (data 2). In case of data 1, the femoral component was flexed from 30 deg to 0 deg by one deg per a frame. In case of data 2, the femoral component was rotated from -10 deg to 10 deg by one deg per a frame. Also, for comparison, data 1 and data 2 were analyzed by using a conventional method, which used the estimated parameter set at the previous frame as the initial parameter set. Figure 11 and Figure 12 show the computer-synthesized images of data 1 and data 2, respectively. Figure 13 shows the estimated flexion angle for data 1. And, Figure 14 shows the estimated internal/external rotation angle for data 2. The absolute mean estimation error for data 1 using the proposed method was 0.24 deg, and using the conventional method was 0.44; for data 2, using the proposed method was 0.31 deg, and using the conventional method was 0.39. These results introduced that the proposed method estimated the knee joint angles which were almost same as the truth values, and the estimation errors of the proposed method were smaller than those of the conventional method.

Figure 15 and Figure 16 show a comparison of initial parameter sets estimated between the proposed method and the conventional method. Figure 15 shows the flexion angle of the initial parameter set for data 1, Figure 16 shows the internal/external angle of the initial parameter set for data 2. As shown in these figures, the proposed method predicted the initial parameters close to the truth values by using Kalman filter. By setting the initial parameter close to the truth value, the estimation accuracy was improved.

V. Conclusion

This paper has proposed a kinematics analysis system of the implanted knee *in vivo* using DR images. The proposed method takes into account continuous movement of the knee implant with Kalman filter. By predicting initial parameter sets close to the global solution using Kalman filter, 3-D pose/position of the knee implant was estimated with high accuracy. The experimental results for computer-synthesized DR images showed that the mean estimation accuracy of flexion angle was 0.24 deg and of rotation angle was 0.31 deg. The computation time was about 4 min a frame by using a computer (CPU: Intel Core2 Quad 2.66GHz, RAM: 4GB). In the future, we will shorten the computation time, and will investigate estimation performance of the proposed method through a large number of experiments.

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