Automated 2D/3D Image Matching Technique with Dual X-ray Images for Estimation of 3D *In Vivo* Knee Kinematics

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Abstract

Quantitative information of a three dimensional (3D) kinematics of joint is very useful in knee joint surgery, understanding how knee kinematics related to joint injury, impairment, surgical treatment, and rehabilitation. In this paper, an automated 2D/3D image matching technique was developed to estimate the 3D *in vivo* knee kinematics using dual X-ray images. First, a 3D geometric model of the knee was reconstructed from CT scan data. The 3D *in vivo* position and orientation of femoral and tibial components of the knee joint could be estimated by minimizing the pixel by pixel difference between the projection images from the developed 3D model and the given X-ray images. The accuracy of the developed technique was validated by an experiment with a cubic phantom. The present 2D/3D image matching technique for the estimation of *in vivo* joint kinematics could be useful for pre-operative planning as well as post-operative evaluation of knee surgery.

Key words : image matching, *in vivo* kinematics, knee joint, total knee arthroplasty,

Ⅰ. INTRODUCTION

Total knee arthroplasty (TKA) is a surgery to be performed for severe degenerative disease of the knee joint. More than 300,000 people undergo this surgery a year in the United States [1]. The goal of TKA is to provide a pain-free knee that allows relatively normal activities and lasts for a long time. It is important that the implant should be inserted in proper position with correct bone alignment because the abnormal kinematics of implanted knees by implant mal-positioning or mal-alignment could cause failure of surgery subsequent to an excessive stress at the implant surface [2,3]. Therefore, quantitative information of a three dimensional (3D) kinematics of the knee joint is very helpful to evaluate the surgical treatment such as planning of size and alignment of the implant and to improve the implant designs by comparing the joint kinematics of patients before and after surgery.

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CT and MRI images are normally used to find 3D kinematics information of the knee joint [4,5]. However, these images are not appropriate for measuring kinematics of the knee joint since the images are taken in static condition. In addition, the imaging environment (a small-diameter cylindrical space in CT/MRI devices) restricts full-motion of joint. Hence, the X-ray fluoroscope has been recently used to analyze the *in vivo* joint kinematics [6,7]. There are many advantages in the X-ray fluoroscope as a measurement tool over CT or MRI. With the X-ray images, the joint kinematics can be measured *in vivo* under dynamic weight-bearing activities. Several researches have applied 2D/3D image matching techniques for assessing the motion of the implants in TKA patients from X-ray fluoroscopic images [2,7-10]. These studies have used the known edge (and silhouette) information of metal components and the knee joint to calculate the similarity between the reconstructed 3D model and the given X-ray images. However, a large library of implant silhouette is necessary to achieve a good result. Moreover, the error in out-of-plane is not small because only a single image is used to find the position and orientation of the implant. Recently, a 2D/3D image matching technique using dual X-ray images has been introduced in order to increase the accuracy in the estimation of out-of-plane motion position and orientation [11,12]. It was reported that the 2D/3D image matching techniques showed better results in accuracy than using a single image.

In this study, a 2D/3D image matching technique was developed to estimate the kinematics of the knee joint based on an automated pixel by pixel comparison of images. The whole estimation of 3D *in vivo* knee kinematics process was performed the following steps. First, the geometric bone models of tibia and femur were reconstructed from CT data. Then, the virtual X-ray images are projected from the geometric models, and the image pixel values are compared directly to pixel values in the dual X-ray images. Next, an optimization algorithm was used to minimize the difference of the pixel values. The accuracy of the present technique was validated by an experiment with a 3D cubic phantom in a known position and orientation.

II. MATERIALS AND METHODS

A. 2D/3D image matching technique with dual X-ray images

For estimating the position and orientation of a 3D object matched with the given dual X-ray images, an automatic 2D/3D image matching technique was developed. Two projection images were obtained from the 3D object by using our own MATLAB code based on the digitally reconstructed radiography method in two perpendicular directions where the given dual X-ray images were taken. The image acquisition geometry which had been set when taking CT images and X-ray images was considered. Figure 1 showed an example of a 3D knee model and the corresponding two projection images. Since the direct pixel by pixel comparison between the projection images and the given X-ray images (Allura Xper FD20, Philips Medical Systems, Best, Netherlands) was performed, both images should be the same size. Here, both the projection images and the given X-ray images were resized into 128×128 pixels.

For the 3D object, a coordinate system could be given. Then, an affine transform representing translations and rotations with respect to the x-, y-, and z-axis could be obtained. The position and orientation of the 3D object were expressed by the translations and rotations in the coordinate system. By varying the amounts of the translations and rotations, the 3D object was translated and rotated by the affine transform automatically and continuously until its projection images were matched with the X-ray images in a given tolerance range. (Fig. 2). The optimization algorithm was used to minimize the error between projection images and the X-ray images to determine the optimal position and orientation. The cost function used in the optimization algorithm was the following root mean square error between the projection image and the given X-ray image:

$$f=\sum_{k=1}^{2}\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}(p_{ij}^{k}-q_{ij}^{k})^2} \qquad (1)$$

where p_{ij}^k and q_{ij}^k denote the (i,j)-th pixel values of the k-th projection image and the k-th X-ray image, respectively, and m and n are the numbers of horizontal and vertical pixels of images (Here, $m= n$=128). The sequential quadratic programming method was utilized in the optimization algorithm to

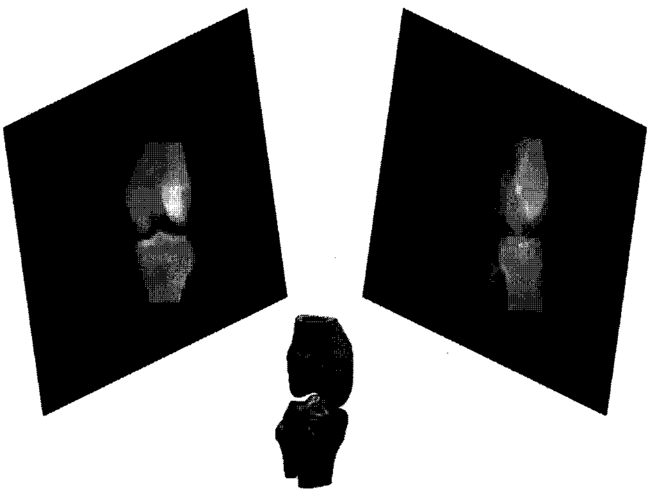


Fig. 1. 3D knee model and the corresponding two projection images

minimize the error between projection images and the X-ray images to determine the optimal position and orientation.

In order to validate the accuracy of the developed 2D/3D image matching technique, the image matching of a cubic phantom was performed. A cubic phantom with a dimension of 64 mm × 64 mm × 64 mm was used. Two virtual X-ray images were taken from two perpendicular directions in a known position and orientation by using the MATLAB code for projection. Then, the developed technique was applied with the cubic phantom model and the two virtual X-ray images to find the position and orientation of the phantom. The accuracy of the present technique was estimated by comparing estimated the position and orientation with the original values. In addition, the 2D/3D image matching technique with one X-ray image was also tested in order to compare the accuracy to the matching technique with two X-ray images. This accuracy test was repeated three times.

B. 3D reconstruction of knee model

In this study, the 3D knee joint models were reconstructed from CT data. The CT images were scanned by 1 mm slice over the range of 128 mm (superior to posterior) of the knee joint (Brilliance-16, Philips Medical Systems, Best, Netherlands). Because the relative position and orientation between femur and tibia is necessary for estimating the 3D knee kinematics, femoral and tibial components should be reconstructed separately (Fig. 3). Thus, the upper half slices and the lower haft slices of CT images were stacked to obtain the 3D models of femoral and tibial components, respectively.

The global coordinate system of the knee joint and the local coordinate systems in both tibial and femoral components were defined to measure the translation and rotation of each component (Fig. 3). The mechanical axis of the knee extending from the center of the hip joint to the middle of the ankle joint was used to define the superior-inferior axis for the femur and tibia. The remaining axes were defined by using conventions reported in the literature [13].

C. Estimation of *in vivo* kinematics of knee

For estimating the position and orientation of the knee joint, the 3D model was matched with the given dual X-ray images by using the developed 2D/3D image matching technique. For each component of the knee joint, the present technique was performed separately. With the obtained results for each component which were all translations and rotations with respect to the x-, y-, and z-axis of the global coordinate system, the tibial and femoral components were combined into the whole knee joint model. Then, the posterior and mediolateral translation of femur with respect to tibia could be estimated. In addition, the flexion angle of the combined knee joint model from the sagittal view was measured based on the consultation of clinicians. In this study, three clinical cases with various flexion angles of the knee joint were tested.

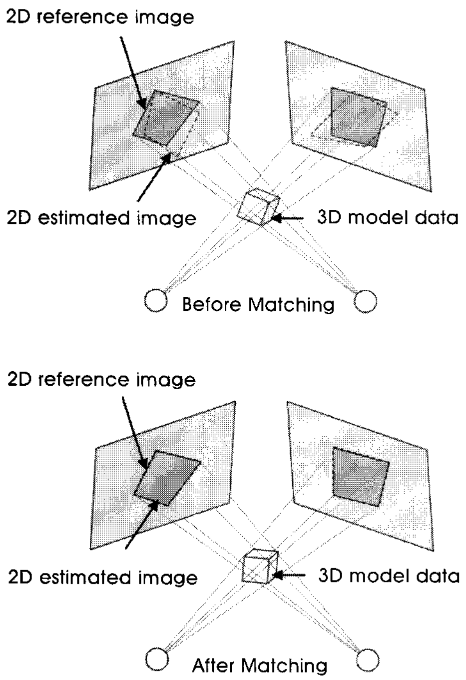


Fig. 2. 2D/3D image matching process

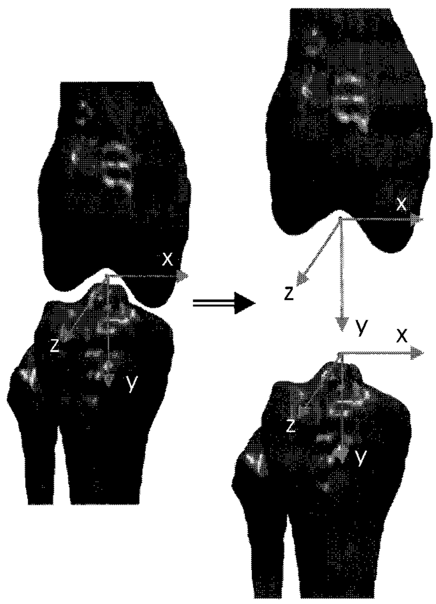
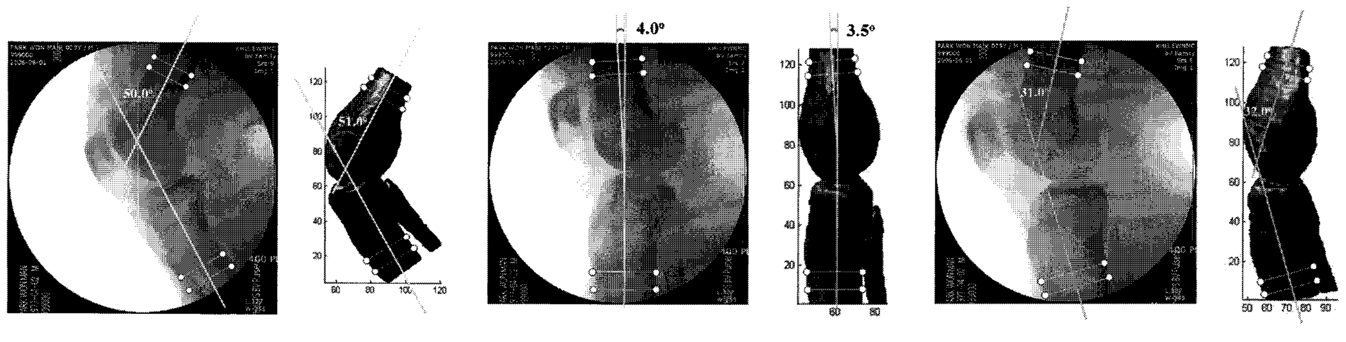


Fig. 3. Reconstructed 3D knee model of femoral and tibial components



(a) Case 1 (b) Case 2 (c) Case 3

Fig. 4. The 3D knee models matched with the given dual X-ray images shown from sagittal view and the flexion angles

III. RESULTS

For the validation of the developed image matching technique with the cubic phantom, three different cases for position and orientation of the cubic phantom were tested. With dual X-ray images, the maximum position errors were 0.03 mm, 0.08 mm, and 0.02 mm and the maximum orientation errors were 0.00°, 0.04°, and 0.03°, in the x-, y-, and z-axis, respectively. With a single image, the maximum position errors were 3.00 mm, 5.00 mm, and 0.03 mm and the maximum orientation errors were 0.03°, 2.58°, and 3.05°, in the x-, y-, and z-axis, respectively. The searching times for optimal solution in the optimization algorithm were approximately 10 minutes with dual X-ray images and 3 minutes with a single X-ray image.

In this study, three clinical cases were investigated to estimate the *in vivo* kinematics of the knee joint. The relative *in vivo* kinematics of the femur were measured as the posterior translations were 3.0 mm, 0.0 mm, and 2.0 mm, respectively and the mediolateral translations were 0.9 mm, 0.0 mm, and 0.1 mm, respectively. In addition, the flexion angles of the knee joint from the sagittal view were 51.0°, 3.5°, and 32.0°, respectively while the angles measured from the given X-ray image were 50.0°, 4.0°, and 31.0°, respectively (Fig. 4). The searching times for optimal solution in the optimization algorithm were approximately 10 minutes.

IV. DISCUSSION AND CONCLUSION

In this paper, an automated 2D/3D image matching technique was developed to estimate the position and orientation of femoral and tibial components from dual X-ray images. The estimated result was used to determine the *in vivo* kinematics of the knee joint. Since the abnormal kinematics of the knee joint could influence the surgical outcomes of TKA, accurate estimation of *in vivo* kinematics of the knee joint would be valuable for pre-operative planning and post-operative evaluation [2,3]. However, a single image is not enough to estimate the out-of-plane kinematics with a single image, thus dual images were used to increase the accuracy of quantification of knee joint kinematics.

X-ray images have been clinically used to find the 3D *in vivo* knee kinematics. First, 2D/3D image matching technique by using a single X-ray image have reported, however, those techniques have a limitation of methodology in detecting out-of-plane translation and rotation though the in-plane accuracy was acceptable: the position errors in out-of-plane were up to 4.0 mm while those in in-plane were below 0.5 mm [3,14]. Hence, dual images have been recently used in the matching technique to improve the out-of-plane accuracy [11,12]. The accuracy in this paper was comparable with the previous literatures: In the accuracy test, the position error in the case of using dual images was below 0.1 mm regardless of the out-of-plane and the in-plane while the out-of-plane error was 5.0 mm in the case of using a single image. Therefore, the 2D/3D image matching technique with dual images was indispensable for the highly accurate estimation of *in vivo* kinematics of the knee.

Though the posterior and mediolateral translations during the flexion and extension motion were closely related with the stability of the knee joint regarding clinical outcomes after TKA, it is difficult to measure *in vivo* translations. Hence, we tried to measure such translations in this study as parameters of *in vivo* kinematics of the knee joint.

Since the present technique was processed by comparing pixel values between images directly, the resolution of the X-ray images was a very important factor to achieve the accurate estimation. In this study, the X-ray image of the cubic phantom in the accuracy test had clearer edge than those of the knee joint, so accuracy itself of the present technique was much higher (below 0.1 mm in translation and 0.04° in rotation) in comparison with the case of the knee joint (up to 1.00° in rotation) as in [12]. To increase the accuracy of the present technique dealing with the knee model, the clearness of X-ray images and the reconstructed 3D knee model should be improved. The threshold filter will be used to enhance the CT data and X-ray images.

There have been 2D/3D image matching techniques operated manually [2,9-11,15]. The 3D object was manually translated and rotated in a virtual space until the projection images were well matched with the given X-ray images. Though the accuracy of those manual matching techniques by a well-trained operator was acceptable, the matching process took long time (several hours) and was dependent on the skill and condition of each operator. Recently, automated image matching technique has developed by applying optimization algorithms based on the comparison of the boundary of images [14,16]. In this study, the optimal position and orientation were obtained by the direct pixel by pixel comparison. In general, the direct image comparison method has several advantages: 1) not to require a segmentation of the image to detect edge of the 3D object, 2) easy to apply the method to the object without very clear edges such as bone, and 3) easy to implement and modify the algorithm. In addition, the root mean square error between images by pixel by pixel comparison is one of the easiest cost functions to utilize in the optimization algorithm among several direct image comparison methods. Since the searching time for optimal solution in the optimization algorithm was approximately 10 minutes, the present automated technique is capable to accelerate the matching process and stabilize the repeatability.

The 2D/3D image matching technique in this study is a powerful tool for the accurate determinations of 3D position and orientation of the knee joint and could provide informative characterization of implant designs and surgical options of the knee surgery. The advantages of our study are the accurate estimation of the 3D knee joint kinematics including out-of-plane motion by using dual X-ray images and the automated process by the optimization algorithm. Furthermore, the present technique could be applied to the studies about 3D dynamic *in vivo* kinematics of other musculoskeletal joint.

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