Development of three-dimensional leg alignment assessment system and its application to the evaluation of component position after total knee arthroplasty

Introduction: Component position and postoperative limb alignment in total knee arthroplasty have been evaluated mainly by biplanar x-ray in antero-posterior (A-P) and lateral view. However, rotational position of components cannot be evaluated by the usual two-dimensional x-ray despite that rotational position of components deeply influences knee kinematics including patella tracking. We have developed the three-dimensional leg alignment assessment system by use of biplanar (A-P and 60-degrees oblique) computed radiography (CR) in standing position. The imaging method of bone model and component model was adapted to the system for application to the three-dimensional evaluation of component position for total knee arthroplasty (TKA). This study introduces the system and investigates the accuracy of the system.

Materials and methods:

1. Three dimensional leg alignment assessment system: A biplanar (A-P and 60-degrees oblique) long leg (from femoral head to ankle joint) CR image was simultaneously taken in standing position by use of the special made cassette holder with an angle of 120 degrees. The holder has a mobile cover for simultaneous projection. Using the camera calibration technique, the three-dimensional position of each X-ray film can be calculated by digitizing the markers of the calibration frame. The maximum error of the camera calibration technique is 1.0 mm and mean error is 0.5 mm. The CR image can be transferred to the personal computer. The reference points are digitized, femoral side: femoral head and bilateral posterior condyles of femur as a spherical shape, and the tibial side: proximal and distal joint surface and line of midpoints of tibia and fibula shaft. By this digitizing, the anatomical coordinate system is established in a biplanar X-ray images. Then the surface of femoral and tibial shaft are digitizing at each 10 percent intervals.

Definition of the anatomical coordinate system: (femur side) Origin: Mid point of centers of spherical fittings on femur side. X-axis: Axis along the line having centers of spheres fitting to femoral condyles. Y-axis: Axis obtained vector production by X-axis and the line having Origin and center of femoral head. Z-axis: Axis obtained vector production. (Tibia side) Origin: Midpoint of proximal tibia joint. Z-axis: Axis connecting the mid point of distal tibial joint to the mid point of proximal tibial joint. Y-axis and X-axis: Same as that of femur. The projection matrix of the three-dimensional computed tomography (CT) model is automatically deformed and superimposed by fitting technique in the biplanar x-ray images. By this technique, the approximation of three-dimensional shape and position of the subject is possible and anatomical parameters such as femoral ante-version, posterior condyle axis, concavity of bony shaft, etc. can be evaluated.

2. Three-dimensional evaluation of component position for TKA: A long leg biplanar x-ray image is taken using the system described above preoperatively and the three-dimensional bone models are deformed and fitted to the femur and tibia of the patient. Then the approximated bone models are saved in the computer. After the TKA, long leg CR images are taken by similar manner and downloaded to the computer and the reference points are digitized. The projection matrix of the approximated bone models saved preoperatively are superimposed in the postoperative biplanar CR image so that the surface shape and reference points of the models and postoperative images are matched. Then the projection matrices of the three-dimensional model of femoral and tibial component are superimposed on the component potion in the CR images so that the surface contour of the models and component images in the CR are matched. The relative position of the components in the bone is calculated from the relation between the anatomical coordinate system and the component coordinate system that is previously installed in the component model.

3. Examination of the accuracy of the image fitting technique (bone models): Four knees (4 patients) that were planned to undergo TKA were examined. Before TKA, a long leg (from femoral head to ankle joint) CT and CR of all knees were taken and the approximated three-dimensional bone models were made by use of image fitting technique described above and saved in the computer. The CT images of each patient were digitized and the three-dimensional bone model was reconstructed and saved in the computer as “personal bone model”. After TKA, a long leg CR was taken again and the three-dimensional evaluation of component position was performed using the method described above (2). In order to examine the error in the deformation and fitting process of bone model, the three-dimensional evaluation of component position of all knees were performed using the superimposing of the personal bone model on the femur and tibia in the postoperative CR image, instead of deformation and fitting of bone model. Then the results of the method using deformation and fitting technique were compared to the results using the superimposing of the personal bone model.

4. Examination of the accuracy of the image fitting technique (components): A femoral and a tibial component (Genesis 2, Smith and Nephew, TN, USA) were fixed on the special made table that can be accurately rotated and tilted. The components were accurately tilted medially and laterally and rotated externally and internally in 5 degrees. The CR images were taken in each pose using the system described above (2). In order to examine the error in the deformation and fitting technique, the approximation of the personal bone model was 0.5 ± 0.3 degrees in lateral tilting, 0.6 ± 0.3 degrees in antero-posterior tilting, and 0.5 ± 0.4 degrees in rotation in femoral component and 0.6 ± 0.3 degrees in lateral tilting, 0.8 ± 0.3 degrees in antero-posterior tilting, and 1.8 ± 1.9 degrees in rotation in tibial component.

2. Accuracy of the image fitting technique (components): femoral component: The difference of evaluated angles of the component were 0.24 degrees in lateral tilting, 0.06 degrees in medial tilting, internal rotation in 0.43 degrees, and 0.14 degrees in external rotation. The maximum error was 0.24 degrees. The tibial component: The difference evaluated angles of the component were 0.14 degrees in lateral tilting, 0.08 degrees in medial tilting, internal rotation in 0.35 degrees, and 0.37 degrees in external rotation. The maximum error was 0.37 degrees.

Discussion: Even though computer assisted surgery and navigation of positioning of TKA became popular, the evaluation of positioning of TKA is still routinely done in two dimensions. We have developed three-dimensional leg alignment assessment system using the biplanar long leg CR in standing position. By the application of image fitting technique of bone model and component model to this system, the three-dimensional evaluation of component position for TKA became to be easy. In this study, the accuracy of the evaluation of three-dimensional component position for TKA was examined using the system. The maximum error of the image fitting technique was less than 1 degree in all directions except for only in rotation in tibial component. This was thought to be good enough for clinical application. In tibia, the anatomical reference points are less clear compared to femur and there are some difficulties in digitizing. This was thought to be the cause that the error in rotation in tibial component was more than that in the others. Recently, three-dimensional knee kinematics after TKA has been focused by some studies2-7. These studies mainly evaluated and analyzed the relative motion between femoral component and tibial component. However, in order to evaluate the knee motion after TKA accurately, three-dimensional component position relative to the bone should be evaluated because knee kinematics is essentially the relative motion between femur and tibia. Three-dimensional evaluation of component position after TKA with the system we developed may be useful for the analysis of knee kinematics after TKA.

Reference: