The accuracy of image-guided knee replacement based on computed tomography

Our study evaluated the accuracy of an image-guided total knee replacement system based on CT with regard to preparation of the femoral and tibial bone using nine limbs from five cadavers. The accuracy was assessed by direct measurement using an extramedullary alignment rod without radiographs.

The mean angular errors of the femur and tibia, which represent angular gaps from the real mechanical axis in the coronal plane, were 0.3˚ and 1.1˚, respectively. The CT-based system, provided almost perfect alignment of the femoral component with less than 1˚ of error and excellent alignment with less than 3˚ of error for the tibial component. Our results suggest that standardisation of knee replacement by the use of this system will lead to improved long-term survival of total knee arthroplasty.

Optimal alignment of the components is fundamental to the achievement of long-term survival of total knee arthroplasty (TKA). In several large series, ideal positioning of the implant was achieved at best in between 70% and 80% of patients when using intramedullary or extramedullary alignment rods.1-7 An error in the coronal positioning of more than 3˚ significantly increases the rate of failure of the component.2,3 Although systems using alignment rods are becoming more sophisticated, errors in positioning of the components and aligning the limb still occur, because a two-dimensional radiograph is used for pre-operative planning and the surgeon controls placement of the rod intra-operatively.

In order to improve the results of conventional methods for TKA, several computer-navigation systems have been developed including image-free, image-based and fluoroscopic procedures. Excellent radiological results have been reported using these systems.8-10 The accuracy of computer-assisted TKA, however, has not been fully evaluated. Most of the studies have judged the quality of implantation using post-operative antero-posterior and lateral whole-leg radiographs. Radiographic measurement is well known to have a limited accuracy. If the leg is rotated or the patient is unable to extend the knee fully, it is difficult to determine component or axial alignment accurately on a radiograph.11

Our study aimed at evaluating the accuracy of an image-guided knee replacement system based on CT using cadaver specimens. The accuracy of the bone preparation was assessed by direct measurement using an extramedullary alignment rod without radiographs.

Materials and Methods
The accuracy of the image-guided knee replacement system was measured in nine limbs which had been retrieved from five embalmed cadavers. Vector Vision knee 1.1.1 (Brain LAB Inc, Heimstetten, Germany) is an image-guided knee replacement system which is based on data obtained from CT scans of the patient. This system allows meticulous pre-operative planning to be done and facilitates optimal placement of the components using three-dimensional navigation.

Acquisition of CT data. We scanned a 50 mm section of the femoral head, a 200 mm section the midpoint of which was the knee, and a 50 mm section of the distal tibia with a slice thickness of 2 mm. The data were transferred to the navigation system and reconstructed into a three-dimensional model (Fig. 1).

Pre-operative planning. The mechanical axis of the femur was defined as a line drawn from the centre of the femoral head to the midpoint of the Whiteside axis,12 while that of the tibia was determined by a line drawn from the centre of the tibial spines to the centre of the bearing surface of the distal tibia, which is the diagonal intersection point. The varus-valgus alignment of the femoral and tibial components was planned so that the mechanical axis passed...
through the centre of each component perpendicularly. The rotational alignment of the femoral component was planned to be parallel to the surgical epicondylar axis,\textsuperscript{13} while that of the tibial component was aligned to face towards the medial third of the tibial tubercle (Figs 2 and 3). The flexion-extension alignment of the femoral component was perpendicular to the anterior cortex of the distal femur, while that of the tibial component was parallel to the...
Fig. 3
Photographs showing definition of the mechanical axis and rotational landmark for implantation of the tibial component.

Fig. 4a
Fig. 4b
Photographs showing the surface-matching procedure for a) the distal femur and b) the proximal tibia. The surgeon can be seen sampling a point on the bony surface.
existing joint line. The system shows the optimal position and size of the component with virtual simulation using the Press-Fit Condylar Sigma knee system (Johnson & Johnson Professional Inc., Raynham, Massachusetts). Pre-operative planning was completed by finely adjusting the components to the anatomy of the patient allowing for the quality of the bone, the presence of osteophytes and bony defects, the size of the component, its cover of the resulting cut surface, and the post-operative alignment.

**Registration.** A surface-matching algorithm using a passive marker wireless system enables the navigation system to show where the patient is positioned in the operating room and to correlate this with the three-dimensional model. Two cameras emit infrared signals and detect passive markers attached to the patient’s anatomy or the surgical instruments. Patient registration was performed in the following manner.

After the pelvis had been fixed firmly to a vice a reference array was attached to the distal femur. The leg was gently pivoted about the hip in order to find the centre of the femoral head. This procedure allows accurate estimation of the centre of the femoral head to be made for the subsequent surface-matching procedure. Surface registration was then performed until an estimated error of registration of less than 2 mm had been attained (Fig. 4). This was not a particular point error, but a mean between the data-points and the model-points computed by the surface-matching algorithm of the system.

**Navigation.** The distal femoral and proximal tibial cutting guides were fixed with pins and bone cuts were made with a standard saw blade. Then the rotational, anteroposterior and mediolateral position of each component was again navigated and special instruments with reference bars, which were parallel to the mediolateral axes of the components, were implanted. The extramedullary alignment rod was designed to fit these instruments perpendicularly (Fig. 5).

**Measurement.** This was performed on a photograph which was perpendicular to the extramedullary alignment rod (Fig. 6). Confirmation of whether or not a photograph was actually perpendicular to the rod was made by a circular presentation of the rod on the picture. A line, which bisected and was perpendicular to the reference bar, was then drawn on the picture and this represented the mechanical axis of each component. The centre of the femoral head was determined by placing the template of a concentric circle over the femoral head on the picture, while the centre of the bearing surface of the tibia was defined as the diagonal point of intersection. The closest distances from the centre of the femoral head and the centre of the bearing surface of the distal tibia to these lines were measured as gap distances based on the scale. The femoral and tibial lengths...
were also measured. Then angular errors, which represent the angular gaps from the real mechanical axis in the varus/valgus direction, were calculated from these distances by the following formula:

$$\tan(\text{angular error} \, \text{˚} \times \frac{2\pi}{360}) = \frac{\text{gap distance} \, \text{mm}}{\text{femoral or tibial length} \, \text{mm}}$$

**Results**

Table I shows the gap distance and the corresponding angular error. The mean gap distance and the angular error of the femur were $2.0 \pm 1.7 \, \text{mm}$ and $0.3 \pm 0.3^\circ$ (mean $\pm$ SD), respectively while those of the tibia were $5.6 \pm 4.3 \, \text{mm}$ and $1.1 \pm 0.8^\circ$, respectively. The mean estimated error of surface registration was $1.09 \, \text{mm}$ for the femur and $1.74 \, \text{mm}$ for the tibia ($p = 0.005$).

**Discussion**

Our study assesses the accuracy of a CT-based image-guided system using cadavers. The results show that this method of implantation of a knee replacement provides almost perfect alignment of components with an error of less than $1^\circ$ for the femur and excellent alignment with an error of less than $3^\circ$ for the tibia. The accuracy of this system in the coronal plane is adequate for clinical use. In our study the sagittal and rotational planes were not evaluated. Although accurate alignment in these planes is equally
important for obtaining a properly balanced knee, a consensus has not been reached as to the adjustment of the sagittal alignment of the component to the mechanical axis of the femur or tibia. Many surgeons believe that rotational alignment should be adjusted to the bony landmarks in the knee, such as the transepicondylar axis and tibial tuberosity, which can be visualised intra-operatively. Our study has only assessed the accuracy of coronal alignment relative to the mechanical axis, which is the most difficult to achieve with conventional systems.

Registration of the patient is the most important procedure for successful computer-aided TKA. We have achieved better results for the femur than for the tibia. The estimated error of a surface registration of the femur was significantly less than that of the tibia which may be because the area which can be used for surface registration is smaller in the tibia than in the femur. Also the centre of the femoral head was accurately estimated again by pivoting the hip. One tibia showed a gap distance of 15 mm in the post-operative alignment, possibly because we had proceeded with the maximum permissible registration error (2.0 mm) in the process of surface matching. Further investigation is necessary to determine how much error can be tolerated in this step. The manner of surface matching also affects the accuracy of registration. When sampling points, the system recognises a point to be the bony surface, even if articular cartilage or soft tissue lies between the bone and the stylus of the pointer. Care must be taken to identify the bony surface correctly.

Whether CT is necessary for computer-aided TKA is a matter for discussion. Several clinical studies on computer-aided TKA using kinematics-based systems, which have incorporated post-operative radiological examination, have shown improved accuracy of implantation of the prosthesis. The image-free system is able to find the mechanical axis of the leg by intra-operative analysis of the kinematics or by digitisation of bony landmarks. The advantage of the image-free system is that it does not require pre-operative imaging or planning. However, its accuracy in defining the centre of the ankle is inferior to that of the CT-based system, in which it can be seen directly on the CT images. Also, the image-free system is not of value when the pivoting method alone is used to detect the centre of the femoral head in patients with an impaired range of hip movement. Marked deviations from ideal alignment can be almost entirely avoided by using this system.

Our study has some limitations. Firstly, the pelvis was more stabilised than in the clinical situation by the use of a vice during femoral pivoting. At operation the pelvis can be stabilised to some extent by the patient’s own weight and by fixing it with a belt in the operating theatre. Pivoting the hip not only added additional information in this CT-based system and is not vital for success. The method of fixing the pelvis does not seem to affect the results significantly. Secondly, the technique of measurement using photographs still includes some error. The pictures may not be perfectly perpendicular to the rod because their position is only confirmed visually. The parallax of the scale between the centre and the edge of the photograph is another concern. However, the photographs in our study were taken 500 mm away from the subjects and the parallax of the scale between the centre and edge of the photograph is less than 0.05 mm. We did not therefore include the parallax in our measurement. Finally, the quality of the preparation of bone using the image-guided system was not compared with that using conventional methods because in cadaver specimens it is easier to align the conventional rods optimally than in the clinical situation. However, these preliminary experiments on cadavers show that CT-based image-guided knee replacement can improve the accuracy of TKA.

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References