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In vivo kinematics of mobile-bearing knee arthroplasty in deep knee bending motion

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Abstract

The current study aimed to analyze kinematics during deep knee bending motion by subjects with fully congruent mobile-bearing total knee arthroplasties allowing axial rotation and anteroposterior (AP) gliding. Twelve subjects were implanted with Dual Bearing Knee prostheses (DBK, slot type: Finsbury Orthopaedics, Surrey, UK). These implants include a mobile-bearing insert that is fully congruent with the femoral component throughout flexion and allows axial rotation and limited AP translation. Sequential fluoroscopic images were taken in the sagittal plane during loaded knee bending motion. In vivo kinematics were analyzed using a two- to three-dimensional registration technique, which uses computer-assisted design models to reproduce the spatial position of femoral and tibial components from single-view fluoroscopic images. The average femoral component demonstrated 13.4° external axial rotation for 0–120° flexion. On average, the medial condyle moved anteriorly 6.2 mm for 0–100° flexion, then posteriorly 4.0 mm for 100–120° flexion. On average, the lateral condyle moved anteriorly 1.0 mm for 0–40° flexion, then posteriorly 8.7 mm for 40–120° flexion. The typical subject exhibited a lateral pivot pattern from extension to 60° flexion and a central pivot pattern from 60° to 100° flexion, patterns that are not usually observed in normal knees. Subsequently from 100° to 120° flexion, a rollback pattern was reproduced in which bilateral condyles moved backward.

Keywords: Total knee arthroplasty; Mobile-bearing; Kinematics; Fluoroscopy; Two- to three-dimensional registration

Introduction

Mobile-bearing total knee arthroplasty (TKA) was developed in the late 1970s, primarily to reduce the risk of aseptic loosening and polyethylene wear [4,8]. Mobile-bearing knee designs feature full or partial conformity of the superior surface of the mobile-bearing insert with femoral condylar geometry, whereas the inferior surface of the mobile-bearing insert is flat to allow rotation (or sliding) on the polished tibial tray with minimal friction. Conformity with mobility in mobile-bearing TKA allows both minimal contact stress and minimal constraint, which cannot be achieved in fixed-bearing TKA.

Motion of the mobile-bearing TKA is controlled by two factors: the design of the articulation and the retained soft tissues. However, observing the clinical details of how the mobile-bearing TKA behaves in vivo is not easy. Recent studies were aimed at clarifying the basics of physiological knee kinematics under loaded conditions [1,11,17]. Moreover, a three-dimensional (3D) kinematic measurement method has been developed using video fluoroscopy and computer-assisted

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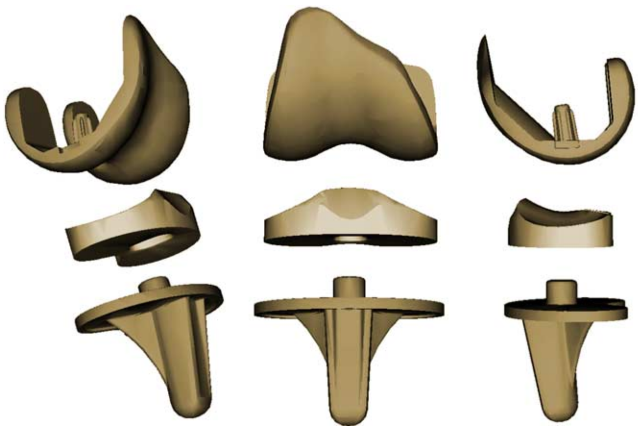

Fig. 1. Three components of the Dual Bearing Knee (DBK) prosthesis system, from oblique (left), anterior (center), and lateral perspectives (right). The top, middle, and bottom portions show the metallic femoral component, mobile-bearing polyethylene insert, and metallic tibial component, respectively.

design (CAD) modeling of metallic knee prostheses [2,12,24] and used to investigate in vivo kinematics after TKA procedures [3,5–7,10,12,15,22,23]. However, these studies concluded that for all TKA designs, including mobile-bearing knees, individual motions observed between TKA subjects and subjects with normal knees could not be reproduced consistently.

In collaboration with Finsbury Orthopaedics (Surrey, UK), we developed a fully congruent designed mobile-bearing knee replacement (the Dual Bearing Knee or DBK prosthesis), which has been in clinical use in Japan and Europe since 1998 (Fig. 1). The aim of the present study was to analyze the in vivo kinematics after DBK TKA in deep knee bending motions. We hypothesized that mobility of this implant in axial rotation and AP translation reproduces the normal knee motion.

Materials and methods

Design of knee prosthesis

The DBK femoral component includes constant radius condyles in the sagittal and coronal planes, completely congruent with the superior articulation of the bearing insert throughout flexion, even under asymmetric loading conditions (Fig. 1). The DBK tibial component has a polished central cylindrical peg to control mobility of the bearing insert. Two types of pit designs are utilized for the undersurface of the bearing insert to fit the tibial control peg. The slotted-type insert allows limited AP gliding between 4 and 6 mm (4 mm for the S-size and 6 mm for the M-size) and free rotation. The holed-type insert, which only allows axial rotation, was not included in this study. The front and rear of the bearing insert have deep recesses for preventing impingement against the patellar tendon and posterior cruciate ligament (PCL) during deep knee flexion. Axial rotation and AP translation of the mobile-bearing insert are controlled passively by soft tissue structures surrounding the knee, including the capsule, musculotendinous units, and multiple ligaments. Excessive AP instability is limited by the stopping mechanism of a slot in the bearing insert.

Subjects

Between August 1998 and September 2001, 141 DBK TKAs were performed in our institute. A total of 11 female patients (12 knee replacements), who underwent successful TKA resulting in >100° knee flexion were chosen for this study as a group of the best performers. All patients agreed to participate in the current investigation. One senior author (TT) performed all the TKA procedures on the subjects using standard operative techniques. The PCL was retained in all subjects, and lateral retinacular releases for poor patellar tracking were not required.

Diagnoses comprised osteoarthritis in 6 knees (5 patients) and rheumatoid arthritis in the other 6 knees (6 patients). Mean patient age at time of fluoroscopic surveillance was 63.0 ± 9.9 years (range, 47–79 years). Mean period between TKA and surveillance was 31.8 ± 10.4 months (14–47 months). Mean postoperative Knee Society knee score [13] was 95.6 ± 4.8 points (84–100 points). Mean postoperative Knee Society function score [13] was 87.1 ± 10.8 points (75–100 points). Mean postoperative coronal alignment was $5.2 \pm 1.8°$ valgus (2–8° valgus), determined radiographically. Mean passive range of motion under unloaded clinical examination was $117.7 \pm 8.3°$ (110–135°). All subjects were satisfied with their outcomes and reported no pain or ligamentous laxity.

In vivo kinematic measurement technique

Under fluoroscopic surveillance in the sagittal plane, each subject was asked to perform sequential deep knee bends under loaded conditions from full extension to maximum flexion. All subjects stood with feet in neutral rotation. Subjects were allowed to hold onto a handrail for safety. Successive knee motions were recorded as serial digital X-ray images ($1024 \times 1024 \times 12$ bits/pixels, 7.5 Hz serial spot images as a DICOM file) using a 12-inch digital image intensifier system (C-vision PRO-T, Shimadzu, Japan) and 1.2–2.0 m s pulsed X-ray beams.

In vivo 3D poses of the DBK prostheses were computed using a two- to three-dimensional (2D/3D) registration technique, which uses CAD models to reproduce spatial postures of the femoral and tibial components from calibrated (including distortion correction) single-view fluoroscopic images (Fig. 2). The registration algorithm proposed by Zuffi et al. [24] was implemented in the current study. The algorithm utilizes a feature-based approach to minimize distances between lines drawn from a contour found in the 2D image to the X-ray source and a surface CAD model with iterative computations. Unfortunately, this

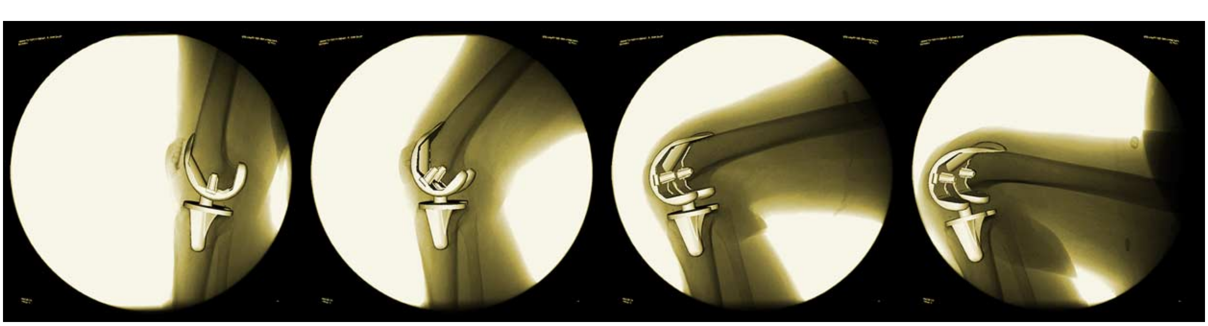

Fig. 2. Results for two- to three-dimensional registration overlaid on a sequence of fluoroscopic images during deep knee bending.

technique could not provide positions of radiolucent mobile-bearing inserts.

Original validation work for the 2D/3D registration technique was performed using phantom experiments. An Optotrak 3020 system (Northern Digital Ink, Ontario, Canada), which is a 3D optical localizer tracking infrared light-emitting-diode (LED)-mounted markers with an accuracy of about 0.1 mm, was used to determine 'grand-truth' poses for comparison with 2D/3D registration described. Femoral and tibial components, which were installed in artificial bones with attached LED markers, were imaged sagittally in 10 different poses and then were digitized using the Optotrak system. Experimental accuracy was assessed by comparing the estimated relative poses between the femoral and tibial component with the 'grand-truth' poses determined by the Optotrak system. The root-mean-square errors of the relative pose for the femoral component in the tibial component coordinate system were 0.2°, 0.6°, and 0.6° for rotation in the coronal, axial, and sagittal plane, respectively, and 0.6, 0.3, and 1.0 mm for translation perpendicular to the coronal, axial, and sagittal plane, respectively. The largest errors of the relative pose were 0.5°, 0.8°, and 0.8° in the coronal, axial, and sagittal plane, respectively, and 0.8, 0.5, and 2.1 mm perpendicular to the coronal, axial, and sagittal plane, respectively. Translations perpendicular to the coronal plane and rotations in the axial and sagittal planes were included in the current kinematic analysis. These error values were better than previously described [24] and were apparently achieved by utilizing higher resolution images.

Coordinate systems and kinematic descriptions

Medial and lateral condyle centers of the femoral component were determined using single radius geometry of each posterior condyle. The coordinate system of the femoral component was defined with the origin at the midpoint of bilateral condyle centers, the axial plane parallel to the distal fixation interface, and the coronal and sagittal planes perpendicular to the axial plane. The origin of the tibial component coordinate system was defined at the center of a control peg, with the tibial tray as the axial plane. In mobile-bearing TKA, surrounding soft tissues control axial rotation with less friction at the femorotibial articulation, so that the tibial component with the individual rotational alignment cannot be considered a referential coordinate system for knee kinematics. To normalize various rotational alignments of the tibial component, the sagittal plane of the tibial coordinate system was adjusted parallel to the individual sagittal plane of the femoral component at 0° flexion. Knee rotations were described using the Grood and Suntay joint rotational convention [9]. All rotations of femoral components were expressed relative to an individual femoral component at 0° flexion in the tibial component coordinate system. Axial femoral rotation was denoted as positive for external rotation and negative for internal rotation. For each of the medial and lateral sides, the closest position of the femur to the tibial tray as the center of quasi-contact was decided by calculating the closest distance between the surfaces of CAD models. AP positions of the femoral condylar centers and the closest positions anterior to the control peg center were denoted as positive, and the posterior positions as negative.

The relative pose of the knee prosthesis was calculated using the 2D/3D registration technique described for every frame of sequential fluoroscopic imaging during the flexion cycle. Calculated pose data were sampled at every 5° from −5° to 120° flexion. The angle of knee flexion for sampled data was permitted error within a range of 1°.

Statistical analysis

All data were expressed as mean ± standard deviation (range, minimum to maximum). Non-parametric Mann–Whitney tests were used for comparisons between AP displacement of the medial and lateral femoral condyles. Values of $p < 0.05$ were considered statistically significant.

Results

The DBK mobile-bearing TKA subjects exhibited axial rotational alignment of the tibial component of 3.1 ± 7.1° (−10.3° to 13.5°), i.e. externally rotated relative to the femoral component at 0° flexion. The minimum flexion angle (at full-extension) under loaded conditions was −1.2 ± 6.0° (−7.2° to 13.8°); the maximum was 112.5 ± 8.4° (98.0–124.5°). The range of motion under loaded conditions was 113.7 ± 9.5° (96.2–131.7°).

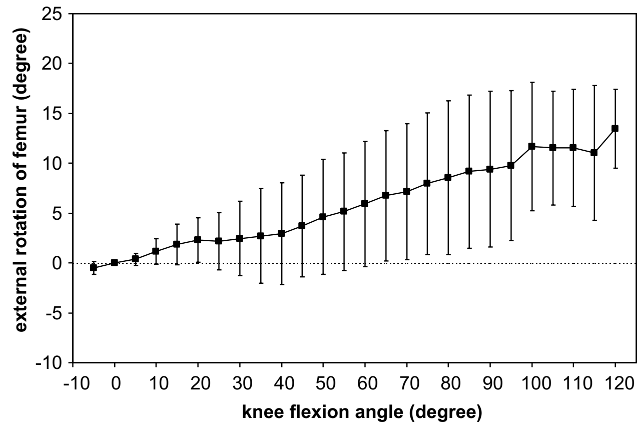

Fig. 3. Femoral external rotation (mean ± SD) of subjects with DBK TKA during deep knee bending.

Axial rotation

Mean axial rotation of the femoral component exhibited gradual external rotation from hyperextension to full flexion (Fig. 3) reaching 13.4 ± 4.0° (9.7–17.6°) at 120° flexion. As exceptions, 2 of the 12 subjects experienced internal rotation within 5° during the flexion cycle, and one subject experienced 19.8° external rotation from 0° to 85° flexion and subsequently 9.7° internal rotation from 85° to full flexion. The remaining nine subjects demonstrated progressive external rotation of the femoral component with progressive flexion. The standard deviation for axial rotation was 0° at 0° flexion, including the effect of normalized individual rotational alignments, increasing to 5–7° during increasing knee flexion (Fig. 3). Mean range of femoral internal/external rotation during the knee flexion cycle was 13.8 ± 5.1° (5.7–21.3°).

Anterior/posterior translation

At 0° knee flexion, both medial and lateral sides exhibited the same AP positions of the femoral condyle centers, −7.0 ± 1.4 mm (−8.9 to −4.8 mm). The average medial condyle center moved 6.2 mm anteriorly to reach −0.8 ± 2.7 mm (−5.7 to 2.6 mm) at 100° flexion, and afterwards moved 4.0 mm posteriorly to reach −4.7 ± 2.8 mm (−6.4 to −1.5 mm) at 120° flexion (Fig. 4). Conversely, the average lateral condyle center moved 1.0 mm anteriorly to reach −6.0 ± 2.8 mm (−10.7 to −2.2 mm) at 40° flexion and subsequently moved 8.7 mm posteriorly

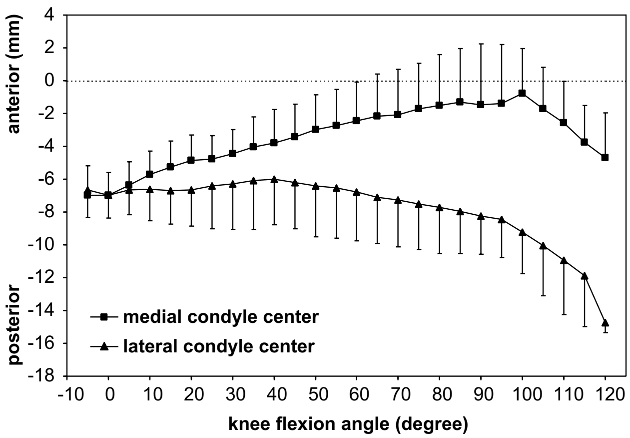

Fig. 4. Anteroposterior translations (mean ± SD) of medial and lateral femoral condyle centers during deep knee bending in subjects with DBK TKA.

to reach −14.7 ± 0.6 mm (−15.1 to −14.0 mm) at 120° flexion (Fig. 4).

AP translations of the closest point on the tibial tray and for the femoral condyle center were almost coincident in all situations for all subjects. Differences between translations were medially 0.1 ± 0.5 mm and laterally 0.0 ± 0.4 mm, indicating that results were essentially identical.

Kinematic pathway

From the results of bilateral condyle positions at each flexion angle, patterns of kinematic pathways were determined (Fig. 5). From extension to 60° knee flexion, the kinematic pattern was a lateral pivot, where the medial condyle moved forward significantly compared with the lesser amount of AP translation for the lateral condyle ($p = 0.001$). From 60° to 100° knee flexion, femoral condyles exhibited a central pivot pattern, where the medial condyle kept moving forward while the lateral started to move back. The difference between magnitude of anterior translation on the medial side and posterior translation on the lateral side was not significant ($p > 0.05$). With more than 100° flexion, kinematics changed into a rollback pattern, where bilateral condyles moved backwards.

Six of the 12 subjects experienced a lateral pivot pattern at the beginning of knee flexion. Five of the 12 (42%) subjects displayed a central pivot pattern within the midflexion angle. Seven of 12 (58%) subjects demonstrated a rollback pattern within the deep flexion angle.

Discussion

The current study analyzed in vivo kinematics of the fully congruent designed mobile-bearing TKA, allowing

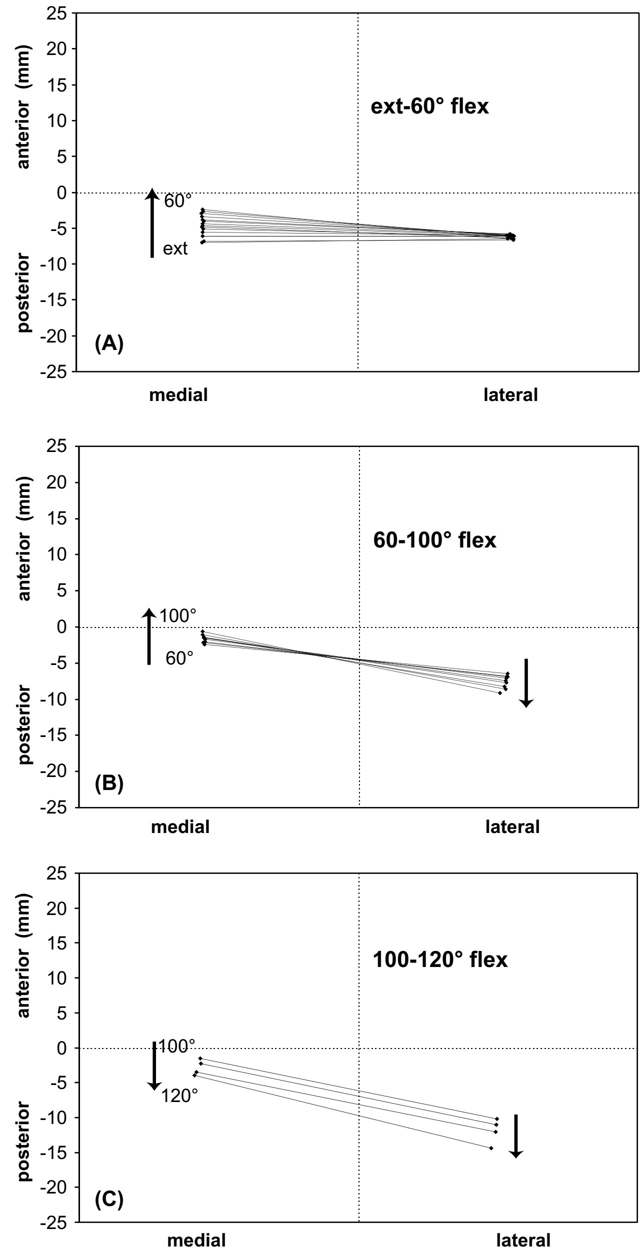

Fig. 5. Average kinematic pathways of medial and lateral condyle centers during knee flexion in subjects with DBK TKA. The average subject experienced a lateral pivot pattern from extension to 60° flexion (A), a central pivot pattern from 60° to 100° flexion (B), and a rollback pattern from 100° to 120° flexion (C).

limited AP translation and free rotation during deep knee bends under loaded conditions. Subjects with DBK mobile-bearing TKA displayed reduced femoral external rotation compared to normal knees and a lateral-to-central pivoting motion never seen in normal knees, and thus our data do not support our hypothesis. With the DBK, the medial condyle exhibited greater anterior translation, while the lateral condyle exhibited reduced posterior translation compared with normal knees. Increased anterior translation of the medial condyle seems to result from reduced constraint of the mobile-bearing on the medial side. The lateral femoral condyle on the mobile-bearing insert might be prevented from shifting backwards by posterior lateral structures such as the popliteal tendon and posterior capsule, contrasting with the lateral femoral condyle of normal knees, which subluxes posteriorly from the tibial plateau in terminal flexion [19]. In the DBK, in which the femoral component displays constant radius condyles, motions of the closest points on the tibial tray and for femoral condyle centers were coincident, so that posterior rollback of femorotibial contacts during low flexion angles was not observed. However, during terminal flexion, a rollback pattern was reproduced in which bilateral condyles moved backwards.

Previous kinematic analyses of normal knees reported the physiological phenomenon of a medial pivoting motion and a posterior femoral rollback during increasing knee flexion [1,8,16,18–20,24]. Normal knees showed 20–29° femoral external rotation with a medial pivoting motion from extension to 120° flexion [1,18,20]. Asano et al. [1] showed that in the normal knee under loaded conditions, the medial center of the femoral condyle moves forward by approximately 5.0 mm, and the lateral center moves backward 17.8 mm during knee flexion from 0° to 120°. In addition, several studies reported that posterior rollback of femorotibial contacts from 0° to 30° occurs predominantly due to the multiradius geometry of normal femoral condyles [1,16,20]. A magnetic resonance imaging study by Nakagawa et al. [19] revealed that normal knees showed bicondylar rollback over 90° of knee flexion, with both medial and lateral condyles moving backwards.

Other mobile-bearing designs, such as the Rotaglide (Corin, Cirencester, UK) [21], self-aligning (SAL) (Sulzer Orthopedics, Baar, Switzerland) and mobile-bearing knee (MBK: Zimmer, Warsaw, IN) [14] utilize pegged tibial trays and slotted polyethylene inserts to allow axial rotation and limited AP translation, similar to the DBK knee. Contrasting with the DBK, the SAL utilizes a partially conforming design with decreased femoral condyle radii that are relatively flat in the coronal plane. The Rotaglide and MBK are fully conforming, with the rotation control pegs on the tibial tray biased posteriorly and anteriorly, respectively. Walker et al. [23] reported in vivo kinematics of the MBK using similar image-matching methodology. The MBK prosthesis demonstrated less axial rotation during deep knee bends than the DBK prosthesis in the present study. Differing kinematics between the two prostheses might reflect differences in design factors, such as the geometry of the mobile-bearing insert and the position of the rotation control peg on the tibial tray, in surgical procedures, in activity conditions during deep knee bending motion, or in referential coordinate systems.

In the present study, in vivo kinematics between radiopaque femoral and tibial components were analyzed using X-ray fluoroscopy and CAD models of metallic components. Using the current technique, we were unable to analyze the kinematics of the radiolucent mobile-bearing inserts, which represent the focus of our interest. During low flexion angles under stable conditions, location of the mobile-bearing inserts could be extrapolated from the location of congruent femoral condyles. However, at high flexion angles or under asymmetrical loading, the position of the insert could not be determined from that of the femoral component. To assess the design of mobile-bearing inserts or AP translation mechanisms between the slot and peg, techniques must first be established to estimate insert positions.

Subjects with DBK mobile-bearing TKA reproduced to some degree femoral external rotation during increasing knee flexion and bicondylar posterior rollback during terminal flexion, due to surrounding soft tissue structures. The geometry of replaced articular surfaces and the mobility of the mobile-bearing insert produced lateral-to-central pivoting motions during the flexion cycle, a phenomenon not typically observed in normal knees. Using the current technique, we characterized the unique kinematics of fully congruent designed DBK mobile-bearing knee prostheses allowing axial rotation and AP gliding. The current kinematic data may provide useful information for future design concepts of TKA.

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References

[1] Asano T, Akagi M, Tanaka K, et al. In vivo three-dimensional knee kinematics using a biplanar image-matching technique. Clin Orthop 2001;388:157–66.

[2] Banks SA, Hodge WA. Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy. IEEE Trans Biomed Eng 1996;43:638–49.

[3] Bertin KC, Komistek RD, Dennis RD, et al. In vivo determination of posterior femoral rollback for subjects having a NexGen posterior cruciate-retaining total knee arthroplasty. J Arthroplasty 2002;17:1040–8.

[4] Buechel FF, Pappas MJ. The New Jersey low-contact-stress knee-replacement system. Arch Orthop Trauma Surg 1986;105:197–204.

[5] Dennis DA, Komistek RD, Hoff WA, Gabriel SM. In vivo knee kinematics derived using an inverse perspective technique. Clin Orthop 1996;331:107–17.

[6] Dennis DA, Komistek RD, Colwell Jr CE, et al. In vivo anteroposterior femorotibial translation of total knee arthroplasty. Clin Orthop 1998;356:47–57.

[7] Dennis DA, Komistek RD, Mahfouz M. In vivo fluoroscopic analysis of fixed-bearing total knee replacements. Clin Orthop 2003;410:114–30.

[8] Goodfellow J, O'Connor J. The mechanics of the knee and prosthesis design. J Bone Joint Surg Br 1978;60:358–69.

[9] Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J Biomech Eng 1983;15:136–44.

[10] Hass BD, Komistek RD, Stiehl JB, et al. Kinematic comparison of posterior cruciate sacrifice versus substitution in a mobile bearing total knee arthroplasty. J Arthroplasty 2002;17:685–92.

[11] Hill PF, Vedi V, Williams A, et al. Tibiofemoral movement 2. J Bone Joint Surg Br 2000;82:1196–8.

[12] Hoff WA, Komistek RD, Dennis DA, et al. Three-dimensional determination of femoral–tibial contact positions under in vivo conditions using fluoroscopy. Clin Biomech 1998;13:455–72.

[13] Insall JN, Dorr LD, Scott RD, Scott WN. Rationale of the Knee Society clinical rating system. Clin Orthop 1989;248:13–4.

[14] Insall JN, Aglietti P, Baldini A, Easley ME. Meniscal-bearing knee replacement. In: Insall JN, Scott WN, editors. Surgery of the knee. 3rd ed. New York: Churchill Livingstone; 2001. p. 1717–38.

[15] Insall JN, Scuderi GR, Komistek RD, et al. Correlation between condylar lift-off and femoral component alignment. Clin Orthop 2002;403:143–52.

[16] Iwaki H, Pinskerova V, Freeman MAR. Tibiofemoral movement 1. J Bone Joint Surg Br 2000;82:1189–95.

[17] Komistek RD, Dennis DA, Mahfouz M. In vivo fluoroscopic analysis of the normal human knee. Clin Orthop 2003;410:69–81.

[18] Kurosawa H, Walker PS, Abe S, et al. Geometry and motion of the knee for implant and orthotic design. J Biomech 1985;18:487–99.

[19] Nakagawa S, Kadoya Y, Todo S, et al. Tibiofemoral movement 3. J Bone Joint Surg Br 2000;82:1199–2000.

[20] Pinskerova V, Iwaki H, Freeman MA. The shapes and relative movements of the femur and tibia in the unloaded cadaveric knee. In: Insall JN, Scott WN, editors. Surgery of the knee. 3rd ed. New York: Churchill Livingstone; 2001. p. 255–83.

[21] Polyzoides AJ, Dendrions GK, Tsakonas H. The Rotaglide total knee arthroplasty. Prosthesis design and early results. J Arthroplasty 1996;11:435–59.

[22] Stiehl JB, Komistek RD, Dennis DA. Detrimental kinematics of a flat on flat total condylar knee arthroplasty. Clin Orthop 1999;365:139–48.

[23] Walker PS, Komistek RD, Barrett DS, et al. Motion of a mobile bearing knee allowing translation and rotation. J Arthroplasty 2002;17:11–9.

[24] Zuffi S, Leardini A, Catani F, et al. A model-based method for the reconstruction of total knee replacement kinematics. IEEE Trans Med Imaging 1999;18:981–91.