Robotic total knee arthroplasty

The accuracy of CT-based component placement

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Background **Accurate alignment of the components in total knee arthroplasty is important. By use of postoperative CT controls, we studied the ability of a robotic effector to accurately place and align total knee arthroplasty (TKA) components according to a purely CT-based preoperative plan.**

Patients and methods **Robotic TKA was performed in 13 patients (6 men) with primary gonarthrosis. Locator screws were placed into femur and tibia under spinal anesthesia. A CT-scan including the femoral head, knee and ankle was performed. In the preoperative planning software, virtual components were positioned into the CT volume. In a second operation, the robot milled femur and tibia with a high-speed milling tool according to the preoperative plan. On the 10th day, CT controls were performed following the same protocol as preoperatively.**

Results **The mean deviation of the postoperative from the preoperatively planned mechanical axis was 0.2° (95% CI: –0.1° to 0.5°). The accuracy of angular component placement in frontal, sagittal and transverse planes was within ± 1.2°, and the accuracy of linear component placement in mediolateral, dorsoventral and caudocranial directions was within ± 1.1 mm.**

Interpretation **Robotic TKA allows placement of components with unparalleled accuracy, but further development is mandatory to integrate soft-tissue balancing into the procedure and make it faster, easier and cheaper.**

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Accurate alignment of the tibial and femoral components in the frontal, sagittal and transversal planes is essential for good results in total knee arthroplasty (TKA). In the frontal plane, the desired mechanical axis of the leg is a straight line from the center of the femoral head through the center of the knee to the center of the ankle. Varus or valgus deviations of > 3° are associated with an increased loosening rate (Jeffery et al. 1991, Ritter et al. 1994). In the sagittal plane, posterior tilting of the tibial component affects the femoral rollback on the tibia, the tension of the posterior cruciate ligament and the range of motion (Wasielewski et al. 1994, Singerman et al. 1996, Piazza et al. 1998). Alignment of tibial components has also been shown to affect postoperative component subsidence and migration (Ryd et al. 1990, Hofmann et al. 1991). In the transversal plane, excessive internal rotation of the components results in increased patellar subluxation and anterior knee pain (Berger et al. 1998, Barrack et al. 2001). Patellofemoral complications and inferior clinical results are also related to an elevated (Figgie et al. 1986) or lowered (Singerman et al. 1996) joint line. However, proper implant positioning in all three planes is sometimes difficult to achieve with currently used oscillating saws and intra- or extramedullary alignment guides (Laskin 2003).

We studied the ability of a robotic effector to accurately place and align femoral and tibial TKA components according to a purely CT-based preoperative plan.

Patients and methods

Robot-assisted TKA was performed in 13 patients (6 men) with primary gonarthrosis. The mean age of the patients was 69 (59–79) years, and the mean preoperative mechanical leg axis was 6° (0°–15°) varus.

The operation was carried out in three steps: placing locator screws, CT-based preoperative planning, and finally the robot-assisted TKA.

Locator screws. Bicortical screws were placed into the distal femur and the proximal tibia through small incisions corresponding to the proximal and distal ends of the later anterior skin incision. A cross with 4 fiducial markers (metallic spheres) was attached to the head of each screw. These were located easily (virtually) in CT images and physically by the robot itself. They were used later on to match the position of the femur and tibia in CT images with their real position during the operation. Placing the locator screws was carried out under spinal anesthesia. The incisions were closed and dressed and the patient was taken to the CT.

CT and preoperative planning. A Philips Mx 8000 IDT scanner was used (Philips Medical Systems, Best, the Netherlands). During CT, the leg was placed in a splint, at full extension. A calibration rod was taped to the leg in order to detect any movement of the extremity during the scan. Three volumes were scanned: the femoral head, the knee joint, and the ankle joint. The field of view was 200–250 mm, and the centers X/Y were identical for all volumes. Scan parameters for the femoral head and the ankle joint were 149 kV, 80 mAs, pitch 0.9 mm, slice collimation 16 × 1.5 mm, and slice thickness 5 mm. For the knee joint, including both locator screws, scan parameters were 140 kV, 150 mAs, pitch 0.66 mm, slice collimation 16 × 0.75 mm, and slice thickness 2 mm.

The data were transferred to the PC-based planning software via the hospital's intranet. With this software (Torch, URS-Ortho, Germany), the surgeon chose the type and size of the components and the PE inlay from menus and positioned them freely by mouse control. The height of the joint line, the varus-valgus alignment of the components in the frontal plane, their slope in the sagittal plane, and their rotation in the transversal plane were set individually in increments as low as 0.1° or 0.1 mm as desired (Figure 1). The software automatically displayed the resulting changes to the extension gap, the flexion gap, the mechanical axis, and the anticipated distances between the bony insertions of the medial and lateral collateral ligaments in extension and flexion. The final position of the virtual components in relation to the locator screws was transferred to the control unit of the robot via PC-card.

Robot-assisted TKA. A conventional medial parapatellar approach to the knee joint was used, integrating the incisions for the locator screws into the anterior longitudinal skin incision. The knee was flexed and rigidly fixed (Figure 2). The robot (CASPAR, URS-Ortho, Germany) probed the fiducial markers attached to the locator screws in femur and tibia, thus matching CT images to reality. The robot then milled the femoral and tibial volumes with a high-speed milling tool attached to its arm. Internal water-cooling and irrigation was integrated into the milling tool, and different milling cutters from 9 mm to 2.5 mm in diameter were used. The fixation frame and locator screws were removed after complete milling, trial implants were placed, and soft tissues were balanced as usual. The components were then inserted manually.

Implants and alignment parameters. In this series, we used the P.F.C. Sigma implant (DePuy Int. Ltd., Leeds, UK), femur and tibia were cemented, and the patella was replaced (oval dome, three pegs) in all cases. A medial release was performed in 9 cases. In 10 cases, the cruciate-retaining P.F.C. model was used. In 3 cases, the cruciate substituting model was used, due to a remaining intraoperative lift-off sign of the tibial trial component in flexion. In the planning software, the mechanical axis was set to 180°, and the tibial and femoral components were aligned perpendicular to the mechanical axes in the frontal plane. In the sagittal plane, the dorsal slope of the tibial components was set to 5°, and the slope of the femoral components to 0°. In the transversal plane, the external rotation of the femoral components was set to a fixed value of 3° against the dorsal epicondylar tangent. The rotation of the tibial components was then aligned with the rotation of the femoral component.

Postoperative CT control. CT examinations of the operated leg were performed on the tenth

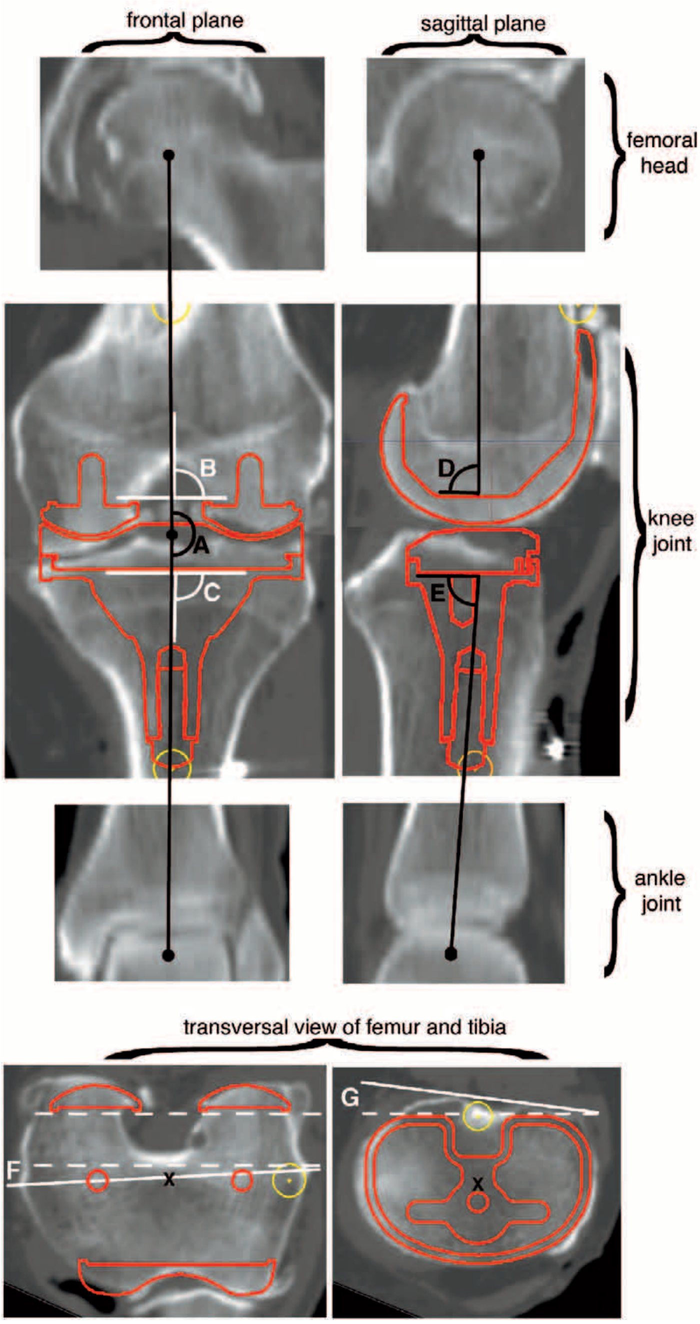

Figure 1. Preoperative CT-scan of the femoral head, the knee and the ankle joint as seen in the planning software. Red outlines represent the tibial and femoral components. The surgeon determines size, position and alignment of the virtual components. The following parameters are adjusted in the preoperative CT to determine the cutter path of the robot:

A. Mechanical axis through the centers of the femoral head, the knee joint and the talus.
B. Femoral plateau angle: angle between the femoral plateau and the mechanical axis of the femur in the frontal plane.
C. Tibial plateau angle: angle between the tibial plateau and the mechanical axis of the tibia in the frontal plane.
D. Slope of the femoral component in the sagittal plane.
E. Slope of the tibial component in the sagittal plane.
F. In the transversal view, the anatomical transepicondylar axis connects the most medial and most lateral prominences of the condyles (solid line). The tangent to the dorsal condyles of the femoral component is shown (dashed line). The angle between these lines determines the rotation of the femoral component.
G. The dorsal tangents to the tibia (solid line) and to the tibial component (dashed line) determine the rotation of the tibial component.
X. In the transversal view, the distances from the geometric centers of the components (marked with an X) to the lateral and ventral cortical borders of femur and tibia are measured to evaluate the placement of components in mediolateral and dorsoventral direction.

Additionally, placement of the components in caudocranial direction was determined by measuring the distance between femoral head center and femoral component center and the distance between tibial component center and the tip of the medial malleolus.

postoperative day, following the same protocol as preoperatively. The data were again transferred into the planning software. The outlines of virtual implants were superimposed on the CT images of the real, implanted components (Figure 3). Considerable artefacts complicated the image overlay on postoperative scans. The position and alignment of the virtual outlines were therefore corrected and adjusted carefully by repeatedly scrolling through the CT data, until the image overlay for the tibial and femoral components was satisfactory in all planes. By going through the whole implant volume in all three planes, enough clearly discernible implant contours were available for accurate

Figure 2. The robotic arm moves with six degrees of freedom. It is draped sterile and equipped with a high-speed milling tool. Threaded Steinmann pins are placed through the proximal tibia and the distal femur from medial to lateral. The pins are clamped taut in a metal frame. The frame and the sterile thigh holder are rigidly connected to the robot itself. Relative motion between the robot and the knee joint is thus minimized. Two sets of reflecting spheres are connected to the robot and the knee joint, and are constantly monitored by an infrared camera which is ready to stop the milling in case of excessive bone motion.

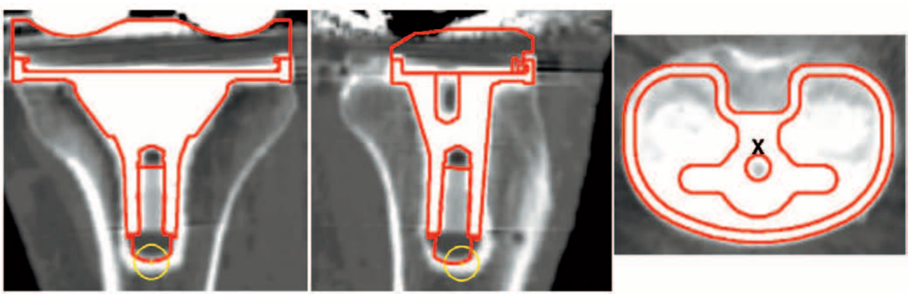

Figure 3. Postoperative CT displaying the implanted tibial component. The outline of the virtual component is positioned and superimposed on the real component in all planes by repeatedly scrolling through the volume, until real and virtual outlines appear congruent. The same procedure is performed for the femoral component, and the relevant parameters are measured for a second time, as seen in Figure 1.

placement of the virtual outlines, despite partial effacement of the implants by artefacts.

The postoperative alignment and position of the components were then measured and compared to those of the corresponding preoperative plan.

The longitudinal axis of the CT scan was identical throughout the complete volume from hip to ankle joint. It was aligned with the mechanical axis of the femur and tibia in the planning software. It was therefore possible to correlate angles and distances measured on different transverse sections of the volume by scrolling upwards or downwards along the mechanical axis. Thus, the dorsal tibial tangent (G, Figure 1) and also the distances from the geometrical center to the cortical borders of the tibial components in lateral and ventral direction (X, Figure 1) was measured 5 mm distally to the tibial cut. Accordingly, the distances between the geometrical center of the femoral component and the cortical bone were measured 40–50 mm proximally to the distal femoral cut. In this way, reliable bony landmarks could be determined on pre- and postoperative scans. The mechanical leg axis was also measured separately on long-leg standing radiographs. The operating time was recorded, and the HSS (Hospital for Special Surgery) knee

Differences between preoperatively planned and postoperatively achieved parameters, as measured on pre– and postoperative CT examinations

	Plane or direction	Mean (95% confidence interval)	ICC inter- / intra-observer
A: mechanical axis	frontal	0.2° (–0.1, 0.5)	0.71 / 0.80
B: femoral plateau angle	frontal	–0.2° (–0.5, 0.2)	0.79 / 0.89
C: tibial plateau angle	frontal	0.2° (–0.1, 0.5)	0.69 / 0.83
D: slope of the femoral component	sagittal	–0.8° (–1.2, –0.3)	0.73 / 0.72
E: slope of the tibial component	sagittal	0.0° (–0.5, 0.5)	0.59 / 0.58
F: rotation of the femoral component	transverse	–0.3° (–0.8, 0.2)	0.78 / 0.86
G: rotation of the tibial component	transverse	0.3° (–0.2, 0.7)	0.01 / 0.58
Distance between			
femoral component center and lateral femur cortex	medio–lateral	0.1 mm (–0.4, 0.6)	0.66 / 0.67
tibial component center and lateral tibia cortex	medio–lateral	–0.2 mm (–0.6, 0.2)	0.73 / 0.82
femoral component center and ventral femur cortex	dorso–ventral	–0.4 mm (–0.8, –0.1)	0.42 / 0.85
tibial component center and ventral tibia cortex	dorso–ventral	–0.5 mm (–0.8, –0.1)	0.61 / 0.60
femoral component center and femoral head center	caudo–cranial	–0.4 mm (–1.1, 0.2)	0.62 / 0.76
tibial component center and tip of medial malleolus	caudo–cranial	0.1 mm (–0.5, 0.7)	0.40 / 0.62

score (Insall et al. 1976) was assessed 6 months postoperatively.

Statistics

Two observers measured pre- and postoperative CT scans twice each at two-month intervals. For each parameter (Figure 1), the differences between the preoperative plan and the postoperative control were calculated. The 95% confidence interval of these differences was calculated ($\bar{x} \pm t_{\alpha/2} \frac{s}{\sqrt{n}}$ $\alpha = 0.05$) to express the ability of the system to position the components as determined in the preoperative plan. Inter- and intraobserver reliability was described by intra-class correlation coefficients (ICC).

Results

Values for linear and angular accuracy, as determined in CT controls, are shown in Table 1. With few exceptions, the inter- and intraobserver reliability of all parameters measured can be regarded as good. 6 months postoperatively, the mean HSS score was 84 (64–96) points. 2 results were graded as fair, 2 as good and 8 as excellent. There was one delayed wound healing, but no further complications were seen. Operating time was 25 (SD 6) min for the insertion of locator screws and 204 (SD 25) min for the robotic TKA. On postoperative long-leg standing radiographs, the mechanical axis was 0° in nine cases, 1° valgus in three cases, and 1° varus in one case.

Discussion

In conventional TKA, intra- and extramedullary alignment guides are widely used but they have limited accuracy. Deviations of ≥ 4° from the desired frontal alignment in approximately 8% of femoral and tibial components have been reported with the use of mechanical alignment guides (Teter et al. 1995a, b). Image-free navigation systems are increasingly deployed in order to improve component positioning. Rigid bodies (e.g. reflecting spheres or LEDs) are attached to the femur, the tibia and the ankle joint, and an infrared camera constantly tracks their position. The joints are then moved through a range of motion, and the mechanical axes are calculated from the optical tracks of the rigid bodies. These systems additionally acquire anatomical landmarks by probing the knee joint with a navigated stylus. Navigated cutting blocks are then attached to femur and tibia, and the resections are carried out with oscillating saws. Encouraging results have been reported for navigated TKA by several groups (Jenny and Boeri 2001, Mielke et al. 2001, Saragaglia et al. 2001, Sparmann et al. 2003). However, current navigation systems rely on cutting blocks and oscillating saws, just as mechanical guides do. Plaskos et al. (2002) compared the planes determined by cutting blocks attached to cadaver femora and tibiae with the resulting planes after bone resection with oscillating saws. They concluded that the inaccuracy of the bone sawing procedure itself contributes 0.6–1.1° (SD) in varus-valgus and 1.8° in flexion-extension to overall variability in implant alignment under experimental conditions. Thus, the optimum alignment would be difficult to achieve even if navigated or mechanical alignment guides could place the cutting blocks in a perfect position. Is there an alternative to the oscillating saw? Studies by Fadda et al. (1998) and Van Ham et al. (1998) demonstrated a superior surface quality and angular accuracy of tibial cuts produced by high-speed milling cutters attached to robotic arms.

The robotic system used in this study allows the surgeon to choose freely among different strategies for placing the components, but only according to bony landmarks. This procedure suits the P.F.C. Sigma knee system, which was designed to insert the components first according to osseous parameters (distal femoral and tibial cuts perpendicular to the mechanical axis, 3° of external rotation for the femoral component against the dorsal epicondyle tangent) and to balance the ligaments later. Implants relying on the balanced flexion-gap method, which rotates the femoral component to form a rectangular flexion gap after cutting the tibia and balancing the ligaments in extension (Olcott and Scott 1999), are not supported at present. This is because an intraoperative tracking of ligament balance and the position of tibia and femur, as in navigated TKA, is as yet lacking. Furthermore, the robot executes the preoperative plan without any possibility of intraoperative changes. Should the necessity for a smaller femoral component or more slope of the tibial component arise during the operation (e.g. in case of a tight flexion gap after insertion of trial components), the surgeon must switch to the manual technique. The excessive operating time in this series indicates the complexity and immaturity of the procedure, the patients being the first robotic TKR at our department with an early version of the fixation frame. Better operating times are possible after a considerable learning curve and adjustment of the instruments (Siebert et al. 2002).

Further improvements of the system are in progress. Surface-based registration and the combination of a robotic effector with navigational tools are being tested in order to replace the locator screws and abandon the necessity for a second operation. The ability to track ligament balance and change implant size and position intraoperatively will improve the versatility of the system. The unwieldy fixation device seen in Figure 2 will be replaced by small clamps for femur and tibia without transosseous fixation, which should reduce the operating time and complexity of the procedure. The need for such a rigid fixation will completely cease to exist once robotic arms not only track, but also follow intraoperative bone motion. In general, systems must become smaller, faster and cheaper without compromising their accuracy. Stepwise technical improvements of the systems must be evaluated in specialized centers. Widespread use is not advisable before the safety, cost-effectiveness and clinical benefits of robotic TKA have been established in controlled studies. As yet, this is not the case. In a thorough review of current computer-assisted TKA, Nizard (2002) has drawn the conclusion that the value of these procedures has not been demonstrated to date, and caution is warranted in the face of enthusiastic reports and presentations.

On the other hand, excellent alignment results and three-dimensional accuracy of robotic TKA have been demonstrated in this study using CT control. In a clinical and conventional radiographic follow-up of seventy patients, Siebert et al. (2002) reported a mechanical axis of 0.8° ± 1° (mean ± SD) and an average operating time of 135 min with robotic TKA. Robotic milling leads to a better surface quality than oscillating saws. Mechanical alignment guides and cutting blocks are obsolete in robotic TKA. New implant geometries can be achieved with robotic milling, opening new possibilities for cementless implants. Clinical results can be related directly to preoperatively planned and accurately conducted alignment parameters (e.g. anterior knee pain with component rotation, ROM with different degrees of tibial slope etc.), thus leading to an increase in our knowledge of these interactions.

The robotic system described here executes the CT-based preoperative plan with unparalleled accuracy, but further effort and technical development is necessary to rid it of some obvious shortcomings.

No competing interests declared.

Barrack R L, Schrader T, Bertot A J, Wolfe M W, Myers L. Component rotation and anterior knee pain after total knee arthroplasty. Clin Orthop 2001; (392): 46-55.

Berger R A, Crossett L S, Jacobs J J, Rubash H E. Malrotation causing patellofemoral complications after total knee arthroplasty. Clin Orthop 1998; (356): 144-53.

Fadda M, Marcacci M, Toksvig-Larsen S, Wang T, Meneghello R. Improving accuracy of bone resections using robotics tool holder and a high speed milling cutting tool. J Med Eng Technol 1998; 22: 280-4.

Figgie H E 3rd, Goldberg V M, Heiple K G, Moller H S, 3rd, Gordon N H. The influence of tibial-patellofemoral location on function of the knee in patients with the posterior stabilized condylar knee prosthesis. J Bone Joint Surg (Am) 1986; 68: 1035-40.

Hofmann A A, Bachus K N, Wyatt R W. Effect of the tibial cut on subsidence following total knee arthroplasty. Clin Orthop 1991; (269): 63-9.

Insall J N, Ranawat C S, Aglietti P, Shine J. A comparison of four models of total knee-replacement prostheses. J Bone Joint Surg (Am) 1976; 58: 754-65.

Jeffery R S, Morris R W, Denham R A. Coronal alignment after total knee replacement. J Bone Joint Surg (Br) 1991; 73: 709-14.

Jenny J Y, Boeri C. Computer-assisted implantation of total knee prostheses: a case-control comparative study with classical instrumentation. Comput Aided Surg 2001; 6: 217-20.

Laskin R S. Instrumentation pitfalls: You just can't go on autopilot! J Arthroplasty 2003; 18: 18-22.

Mielke R K, Clemens U, Jens J H, Kershally S. Navigation in knee endoprosthesis implantation-- preliminary experiences and prospective comparative study with conventional implantation technique. Z Orthop Ihre Grenzgeb 2001; 139: 109-16.

Nizard R. Computer assisted surgery for total knee arthroplasty. Acta Orthop Belg 2002; 68: 215-30.

Olcott C W, Scott R D. The Ranawat Award. Femoral component rotation during total knee arthroplasty. Clin Orthop 1999; (367): 39-42.

Piazza S J, Delp S L, Stulberg S D, Stern S H. Posterior tilting of the tibial component decreases femoral rollback in posterior-substituting knee replacement: a computer simulation study. J Orthop Res 1998; 16: 264-70.

Plaskos C, Hodgson A J, Inkpen K, McGraw R W. Bone cutting errors in total knee arthroplasty. J Arthroplasty 2002; 17: 698-705.

Ritter M A, Faris P M, Keating E M, Meding J B. Postoperative alignment of total knee replacement. Its effect on survival. Clin Orthop 1994; (299): 153-6.

Ryd L, Lindstrand A, Stenstrom A, Selvik G. Porous coated anatomic tricompartmental tibial components. The relationship between prosthetic position and micromotion. Clin Orthop 1990; (251): 189-97.

Saragaglia D, Picard F, Chaussard C, Montbarbon E, Leitner F, Cinquin P. Computer-assisted knee arthroplasty: comparison with a conventional procedure. Results of 50 cases in a prospective randomized study. Rev Chir Orthop Reparatrice Appar Mot 2001; 87: 18-28.

Siebert W, Mai S, Kober R, Heeckt P F. Technique and first clinical results of robot-assisted total knee replacement. Knee 2002; 9: 173-80.

Singerman R, Dean J C, Pagan H D, Goldberg V M. Decreased posterior tibial slope increases strain in the posterior cruciate ligament following total knee arthroplasty. J Arthroplasty 1996; 11: 99-103.

Sparmann M, Wolke B, Czupalla H, Banzer D, Zink A. Positioning of total knee arthroplasty with and without navigation support. J Bone Joint Surg (Br) 2003; 85: 830-5.

Teter K E, Bregman D, Colwell C W, Jr. The efficacy of intramedullary femoral alignment in total knee replacement. Clin Orthop 1995a; (321): 117-21.

Teter K E, Bregman D, Colwell C W, Jr. Accuracy of intramedullary versus extramedullary tibial alignment cutting systems in total knee arthroplasty. Clin Orthop 1995b; (321): 106-10

Van Ham G, Denis K, Vander Sloten J, Van Audekercke R, Van der Perre G, De Schutter J, Aertbelien E, Demey S, Bellemans J. Machining and accuracy studies for a tibial knee implant using a force-controlled robot. Comput Aided Surg 1998; 3: 123-33.

Wasielewski R C, Galante J O, Leighty R M, Natarajan R N, Rosenberg A G. Wear patterns on retrieved polyethylene tibial inserts and their relationship to technical considerations during total knee arthroplasty. Clin Orthop 1994; (299): 31-43.