Robotic Arm–Assisted Unicompartmental Knee Arthroplasty: Preoperative Planning and Surgical Technique

Martin Roche, MD, Padhraig F. O'Loughlin, MD, Daniel Kendoff, MD, PhD, Volker Musahl, MD, and Andrew D. Pearle, MD

ABSTRACT

The goals of computer-assisted surgery (CAS) are to be patient-specific, minimally invasive, and quantitative. CAS can involve preoperative imaging and planning, intraoperative execution, and postoperative evaluation. Ideally, these components are integrated such that sophisticated diagnostic technologies are used to inform a patient-specific surgical plan.

A recently developed CAS/robotic system has the potential to improve alignment in and results of unicompartmental knee arthroplasty. This new robot is "semiactive"; that is, the surgeon retains ultimate control of the procedure while benefiting from robotic guidance within target zones and boundaries.

Surgeons who use the robotic arm–assisted technique described in this article can prepare and then precisely execute a patient-specific computed-tomography–based operative plan. The surgical field is predefined, and the active constraints used by the robotic arm eliminate inadvertent deviation outside this field, thus minimizing iatrogenic morbidity and maximizing bone preservation.

In this article, we detail the preoperative planning and intraoperative technique for robotic arm–assisted unicompartmental knee arthroplasty.

In the United States in recent years, the number of unicompartmental knee arthroplasties (UKAs) performed annually has been increasing consistently. In 1997, approximately 1% of knee arthroplasties were UKAs; in contrast, UKAs represented 6% of all implanted knee arthroplasties in 2000.[1] Results from orthopedic studies have shown that medial UKAs produce good mid- to long-term results.[2]

Despite this recent interest in UKA, significant issues remain. These include early failure of the femoral[3] or tibial[4,5] components. The main cause of early failure is malpositioning of components with overcorrection or undercorrection of limb alignment.[6] Malalignment of the femoral component has been found to cause femoral fracture,[7] patellar impingement, and tibial component loosening.[8] In addition, excessive posterior slope (>7°) of the tibial component has been linked to tibial component loosening,[9] anterior cruciate ligament (ACL) rupture,[9] and abnormal stress forces on the periprosthetic bone.[10] Therefore, though UKA has many benefits, technical difficulties in achieving accurate alignment have impeded widespread adoption of this procedure by orthopedic surgeons.

> **"...the TGS allows surgeons to prepare a patient-specific CT-based preoperative plan that can be executed precisely."**

In a bid to improve UKA outcomes, orthopedic surgeons have begun taking advantage of several technological innovations, including use of computer-assisted navigation and robotics. Navigation has been shown to improve postoperative leg alignment over that obtained in conventional UKA.[11,12] However, direct improvement in implant positioning has so far not been demonstrated in the literature. Although navigation is a powerful visual aid, ultimate surgical outcomes still depend on the mechanical tools used in procedures.

Recently developed robotic systems have tremendous potential to improve the outcomes of procedures such as UKA. Crucially, these new robots are "semiactive"; that is, the surgeon retains ultimate control of the procedure while benefiting from robotic guidance within target zones and surgical field boundaries. These zones and boundaries are determined by preoperative computed-tomography–based (CT-based) planning with continuous intraoperative visual feedback. The system is essentially a marriage of cutting-

Dr. Roche is the Chief Attending Orthopaedic Surgeon, Department of Orthopaedic Surgery, Holy Cross Hospital, Fort Lauderdale, Florida.
Dr. O'Loughlin is Computer-Assisted Surgery Fellow, Dr. Kendoff and Dr. Musahl are Fellows, and Dr. Pearle is an Attending Orthopaedic Surgeon. All are based in the Department of Orthopaedic Surgery, Hospital for Special Surgery, New York, New York.

Address correspondence to: Andrew Pearle, MD, Sports Medicine and Shoulder Service, Computer-Assisted Surgery Center, Hospital for Special Surgery, 532 E 72nd St, New York, NY 10021 (tel, 212-774-2878; fax, 212-774-2798; e-mail, pearlea@hss.edu).

Am J Orthop. 2009;38(2 suppl):10-15.

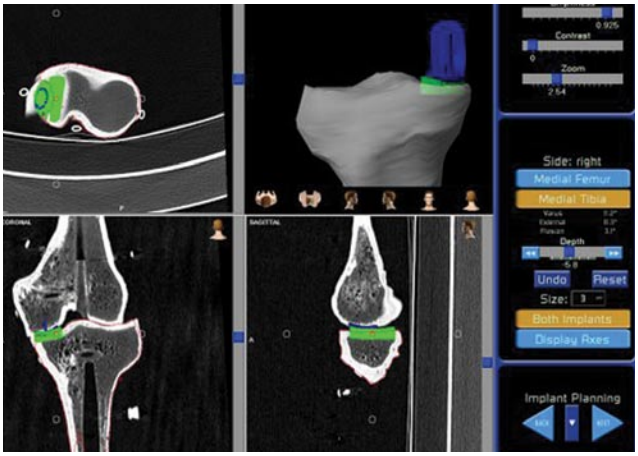


Figure 1. Models of implants are positioned, with corresponding cement mantles on reconstructed bone models, resulting in patient-specific computed-tomography–based planning.

Figure 2. Robot registration is performed after conventional positioning and sterile draping.

edge navigation and robot technology. The combination allows for more accurate reproduction of the preoperative plan of implant placement, which may improve overall leg alignment and reduce iatrogenic morbidity.[13,14] It also allows for rapid progression up the learning curve, which can minimize failures related to surgeon workload.[4]

The fundamental goals of computer-assisted surgery (CAS) are to be patient-specific, minimally invasive, and quantitative. CAS can involve preoperative imaging and planning, intraoperative execution, and postoperative evaluation. Ideally, these components are integrated such that sophisticated diagnostic technologies are used to inform a patient-specific surgical plan. This plan is then programmed into a computer-assisted intraoperative system so that it can be precisely executed. Finally, patient outcomes are tracked quantitatively.

Surgeons who use CAS rely on its quantitative data to supplement their feel and intuition and inform their clinical decision-making. These technologies introduce manufacturing concepts, such as the need for technical specifications with known targets and tolerances, into orthopedic procedures. These concepts are essential to understanding implementation of surgical robotics for UKA. In this CAS application, surgical specifications are used to help determine appropriate implant positions. This plan is then programmed into the robotic system, and the robotic arm aids in precise execution of the operative plan (it should be noted that precise execution of a suboptimal preoperative plan will result in a suboptimal outcome).

In this article, we detail the preoperative planning and intraoperative technique for robotic UKA.

TECHNIQUE

Preoperative Imaging

Preoperative CT scans are obtained for all patients. Scan protocol requires supine positioning with a motion rod attached to the affected leg. One-millimeter slices are taken at the knee joint, and 5-mm slices are taken through the hip and ankle. Images are saved in DICOM (Digital Imaging and Communications in Medicine; Rosslyn, VA) format and transferred to the software of the Tactile Guidance System (TGS; MAKO Surgical Corp., Fort Lauderdale, FL) so that sagittal slices of the distal femur and proximal tibia may be segmented, defined, and recombined to produce 3-dimensional (3-D) models of each. Implant models are then positioned, with corresponding cement mantles on the reconstructed bone models, resulting in patient-specific CT-based planning (Figure 1).

CT-based planning is limited in that soft tissues cannot be visualized with CT. Consequently, guidance for soft-tissue balancing is lacking, only bony alignment can be used for planning, and the plan must be intraoperatively modified to achieve precise gap balancing and long-leg alignment. CT planning allows for assessment of the subchondral bone bed, osteophyte formations, and volume definition of cysts and avascular necrosis.

Preoperative Planning

The preoperative plan is based on 4 main parameters: alignment metrics, 3-D virtual visualization of implant position, intraoperative gap kinematics, and dynamic lower limb alignment monitoring.

Accurate implant positioning requires integrating into the system the precise dimensions of the femoral and tibial prostheses, with their target positions programmed into the preoperative planning software. The implant computer-assisted design (CAD) models are positioned on the 3-D models of the patient's distal femur and proximal tibia, and alignment parameters reported on the computer display unit. This step facilitates visualizing predicted implant congruence and minimizing areas of edge loading through plan adjustments. Feedback regarding alignment metrics and bony anatomy (eg, subchondral bony bed, cortical rim) is continuously displayed. The joint line can be defined and adjusted and the patient-specific slope on the tibia defined. Although the implants are not customized to the patient, implant orientation is patient-specific and includes quan-

Figure 3. A high-speed burr is attached to the distal end of the robotic arm.

Figure 4. A leg holder can be used to keep the limb stable during resection.

titative feedback from both bony and soft-tissue anatomy. Thus, bone resection volumes are defined automatically by the system, and boundaries for the cutting instrument are set to prevent inadvertent surgery to areas outside these predefined zones.

The preliminary plan is based on alignment parameters and 3-D visualization of implant position. During surgery, the plan is modified according to gap kinematic measurements and dynamic lower limb alignment values.

Before surgery, we use the alignment parameters reported by the robotic system (and recommended by the manufacturer) in combination with parameters supported by the literature. Specifically, tibial slope in the coronal and sagittal planes is carefully controlled. The medial tibial plateau typically has varus slope vis-à-vis the mechanical axis of the tibia in patients with medial compartment osteoarthritis. Collier and colleagues[5] demonstrated that correction of this varus slope with the tibial implant can improve survivorship. In addition, more than 7° of posterior slope of the tibial component has been shown to increase the risk for ACL rupture.[9] We therefore recommend placing the tibial components in 2° to 4° of varus and avoiding more than 7° of posterior slope. In patients with ACL deficiency, the posterior sagittal slope of the tibia is maintained between 2° and 5°.

Three-dimensional visualization of implant position ensures proper sizing. For example, we advocate a 2-mm rim of bone surrounding the pocket created for the inlay tibial component. This rim can be planned and measured directly on the 3-D model. On the femur, the prosthesis is sized such that coverage is maintained while symmetric flexion and extension gaps are created. In addition, depth of resection can be planned precisely; 3 mm of tibial bone resection is typically planned. This resection depth can be modified according to intraoperative gap kinematics.

Setup

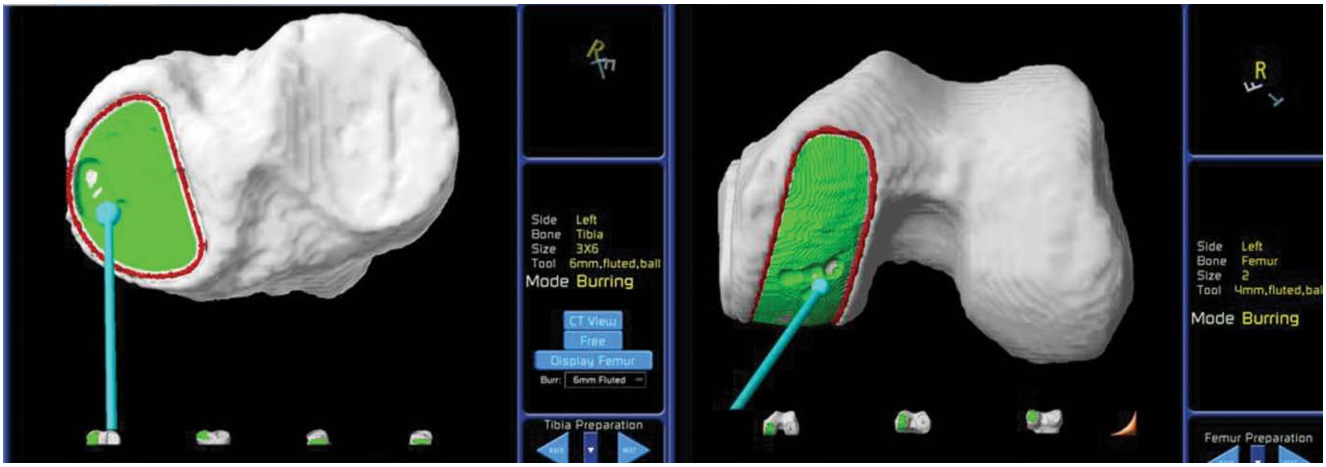
The TGS is positioned before the patient arrives in the OR. Positioning is based on the knee to be operated on and on surgeon preference (right- or left-hand dominant). The line of sight between the robot reference array and the optical camera is approximated before surgery. Once the system is positioned, the robot base unit is secured with brakes to prevent motion.

After conventional positioning and sterile draping of the affected limb, robot registration is performed (Figure 2). The surgeon moves the robotic arm through a defined 3-D path to calibrate its movements and set the center point for the cutting instrument. The femoral and tibial reference arrays are then attached. Bone pins are placed in the femur and tibia, and optical arrays are securely attached. The camera is now positioned to track the robot and leg arrays through all ranges of motion (ROMs). Anatomical surface landmarks are registered before the skin is incised, and the leg is put through full ROM while the appropriate valgus load is applied on the joint. After skin incision, small juxta-articular checkpoint pins are inserted on tibia and femur, and the 2 bone surfaces are registered at these points. We have noted that incisions can be made as short as 2.25 inches in some patients with minimal strain on soft tissue.

> **"The [robotic] arm helps control depth, width, and length of burring with graphical feedback on the navigation monitor."**

Intraoperative Soft-Tissue Balancing and Lower Limb Alignment Monitoring

After intraoperative registration of bony anatomy and implant position target setting, a dynamic soft-tissue-gap balancing algorithm is initiated. Virtual modeling of the knee and intraoperative tracking allow real-time adjustments to be made to obtain correct knee kinematics


Side Left
Bone Tibia
Size 3X6
Tool 6mm,fluted,ball
Mode Burring

Burr: 6mm Fluted

Side Left
Bone Femur
Size 2
Tool 4mm,fluted,bal

Mode Burring

Figure 5. Navigation screen provides permanent graphical feedback on actual and planned cavities based on patient-specific preoperative planning for the tibia and the femur.

and soft-tissue balancing. First, osteophytes interfering with medial collateral ligament function are removed, and capsular adhesions interfering with knee function are relieved. As one indication for UKA is a correctable deformity, removal of these impediments makes it possible to achieve correct leg kinematics and tissue tension during passive manipulation throughout the full ROM with an applied valgus stress. Three-dimensional positions of femur and tibia are captured throughout the ROM with the medial collateral ligament properly tensioned. This provides correct bone spacing (extension and flexion gaps) during implant planning such that, after resection and component implantation, knee mechanics will be properly restored throughout the ROM. The articular surfaces of the components are then adjusted to fill that space throughout the ROM. Once optimized, the plan incorporates alignment metrics, implant congruence, and gap kinematics in a highly individualized fashion. Finally, any varus deformity is manually corrected with application of a valgus force to the knee, while lower limb alignment is simultaneously monitored and recorded by the navigation system. As the virtual components are optimized to fill the space necessary to correct this deformity, final lower limb alignment is reliably predicted. We target final lower limb alignment of approximately 2° of varus. Care is taken to avoid undercorrection (final alignment, <8° varus) and overcorrection (final alignment in valgus) of long-leg alignment.[15]

Robotic Arm

The TGS has 3 components: robotic arm, optical camera, and operator computer. The end of the robotic arm has 5° of freedom, and its movement is restricted to the incision site by the 3-D virtual boundaries preset in the software at the time of customized preoperative planning; intraoperative adjustments of that plan are made to ensure correct soft-tissue balancing. The optical camera is an infrared system. The system computer (housed in a customized cart) runs the software that drives the surgical plan.

A high-speed burr is attached to the distal end of the robotic arm (Figure 3). The surgeon moves the arm by guiding its force-controlled tip within the predefined boundaries. The robot gives the surgeon active tactile, visual, and auditory feedback during burring. While inside the volume of bone to be resected, the arm operates without resisting. As the burr approaches the boundary, auditory feedback (a series of warning beeps) is given, and, when the burr reaches the boundary, the arm resists that motion and keeps the burr within the accepted volume. Thus, the arm effectively is a 3-D virtual instrument set that precisely executes the preoperative plan. In addition, excessive force at the limits of the 3-D cutting volume or rapid movement of patient anatomy immediately stops the cutting instrument to prevent unintentional resection outside the defined implant area.

Unlike other active and semiactive robot systems, the TGS does not require rigid fixation of the robot to the patient. Rather, osseous reference markers track the position of the tibia and the femur. As the bones move during surgery, the haptic 3-D resection volume moves coincidently. During resection, a leg holder is used to keep the limb stable while allowing optimal positioning of the knee to ensure access to the targeted surfaces (Figure 4).

Burr System

A hand-powered or foot-pedal–operated high-speed (75 rpm) electric burr (eMax2; Anspach Effort, Palm Beach Gardens, FL) is used for resection. Burrs of 3 sizes are used: a 6-mm-diameter spherical burr for rapid removal of major bone material to allow insertion of the femoral prosthesis post; a 2-mm-diameter spherical burr for fine-finishing, including fine-finishing of the edges and corners of the resection area; and a 1.2-mm router for deep milling of the mini–femoral keel canal. All burring is visualized on a computer screen display, which shows the 3-D models of distal femur and proximal tibia. The models are color-coded such that the resection area color—green in the current version of the software—is different from the color of the surrounding bone. If the robotic arm goes 0.5 mm outside the

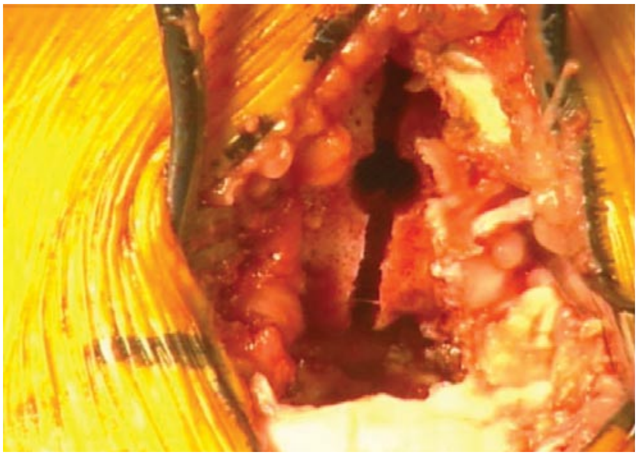
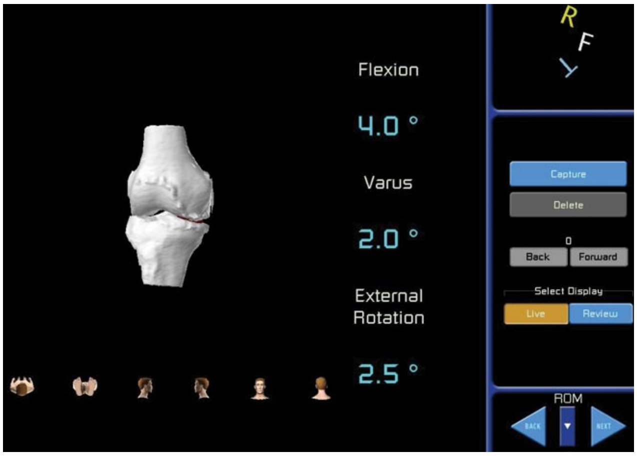


Figure 6. Both cavities can be milled completely, and the implants inserted precisely.



Flexion 4.0 °

Varus 2.0 °

External Rotation 2.5 °

Figure 7. Long-leg alignment displayed dynamically on the computer monitor can be used to track final alignment.

green area, red appears on the display, and the arm stiffens progressively; if the arm goes any farther outside the green area, the burr stops revolving automatically.

Implant

The StelKast Unicondylar Knee System (StelKast Corporation, McMurry, PA) consists of a nonmetal-backed polyethylene tibial inlay insert, a cobalt-chromium femoral component, and a femoral implant with a mini-stem. An alternative implant, with a modular metal-backed tibial onlay and a cobalt-chromium femoral component (MAKO Surgical Corp., Fort Lauderdale, FL), is also available.

Operative Technique

The robotic arm assists the surgeon during defined burring of the tibial and femoral surfaces. The arm helps control depth, width, and length of burring with graphical feedback on the navigation monitor. It is recommended that the arm be used to prepare the tibial cavity before addressing the femoral surface so as to allow easier access to that surface, particularly its posterior side. The arm also allows intraoperative conversion to a metal-backed onlay implant.

With use of only soft-tissue retractors, initial burring of tibial and femoral surfaces (including the femoral post hole) is performed with a 6-mm spherical burr; fine-milling is performed with the 2-mm spherical burr. The femoral keel slot is burred with the 1.2-mm fluted router.

The navigation screen continuously shows the planned cavity versus the actual cavity (Figure 5). Once both have been completely milled (Figure 6), femoral and tibial component trials are inserted, and a complete flexion-extension arc is performed. Dynamic long-leg alignment is displayed on the computer monitor so that final alignment can be tracked (Figure 7).

Finally, once the implant is satisfactorily positioned, both implant components are cemented, and a final ROM of the knee joint is executed so that original, trial, and final implant kinematics and knee alignment can be compared. Before site closure, the mini-checkpoints and bone reference arrays are removed.

Discussion

The combination of computer-assisted navigation and robotics has the potential to allow UKAs to be performed more accurately than ever before possible. Thus, this marriage of technologies may herald resurgence of a technique that had lost favor because of outcomes that were unsatisfactory relative to those of traditional procedures (eg, total knee arthroplasty). When new technology is introduced, we must determine whether it is “enabling,” whether it enhances the effectiveness and the accuracy of a procedure. If the technology produces outcomes that are favorable relative to those of traditional techniques, then the decision becomes whether further use of the enabling technology is warranted given the benefits (outcomes) and costs (financial costs, increased operating time, and need for specially trained personnel).

Previous studies with an alternative robotic system for UKA have had promising early results. In a prospective clinical study, Cobb, Rodriguez, and colleagues[13,14] found significant improvement in implant placement and leg alignment with use of a semiactive robotic system. That system, however, has its limitations. Unlike the TGS, it requires direct mechanical fixation of robot to bone. Problems associated with this setup include fracture and/or soft-tissue injury caused by robot weight, motion, and intrusion into the surgical field; in addition, the system is not amenable to minimally invasive techniques. With the TGS, standard navigation reference markers are used to facilitate dynamic tracking of both femur and tibia; robotic motion can be independent of patient position and movement; and minimally invasive approaches are easily accommodated.

Despite the evident advantages of using computer-assisted navigation for UKA, the procedure may be limited by imprecise tools. This is not the case with the TGS. Compared with the traditional oscillating saw, the burrs used with the robotic arm allow for more precision in bone resection (in accordance with a patient-specific operative plan), for fashioning a custom or press-fit cavity for inlay implants, and for maximizing bone preservation, which is critical should a revision procedure or conversion to total knee arthroplasty be necessary.

We believe that CT-based planning with construction of 3-D CAD models of the distal femur and the proximal tibia results in more precise implant positioning and simulation of implant overlap during knee flexion and extension, which allows for dynamic gap kinematic assessment. Consequently, the surgeon can alter the plan as the procedure progresses and can include more patient-specific data during surgery. As Cobb and colleagues[13] showed with their Acrobot system (Acrobot Company, Ltd., London, United Kingdom), a more accurate preoperative plan can be achieved with robot assistance. They found that the tibiofemoral alignment achieved with use of the robot was consistently within 2° of the planned position. (A similar degree of accuracy was achieved in only 40% of those cases when conventional techniques were used.) Such accuracy may affect outcomes in terms of mid- and long-term survivorship and function. For example, as previous studies have shown, compared with conventional UKA, minimally invasive UKA has had higher revision rates and more frequent aseptic loosening because of increased difficulty in identifying bony landmarks and achieving accurate alignment.[11,12]

In conclusion, the TGS allows surgeons to prepare a patient-specific CT-based preoperative plan that can be executed precisely. The surgical field is predefined, and inadvertent deviation outside the field is prevented by active constraints of the robotic arm, thus minimizing iatrogenic morbidity and maximizing bone preservation. Bone resection is precisely performed with a succession of different sized burrs; these are used to facilitate cavity creation and implant placement. This precision, versus what is possible with conventional techniques, may improve the likelihood of satisfactory clinical outcomes. Appropriate clinical trials are warranted to establish the efficacy of this system so that its potential can be realized.

AUTHORS' DISCLOSURE STATEMENT

Dr. Roche wishes to note that he is a paid consultant and designer for MAKO Surgical Corp. and for DePuy Orthopaedics. The other authors report no actual or potential conflict of interest in relation to this article. The authors acknowledge the grant from MAKO Surgical Corp. in support of publishing this supplement.

REFERENCES

1. Millennium Research Group. *US Markets for Reconstructive Devices 2001.* Toronto: Millennium Research Group; 2002.
2. Berger RA, Meneghini RM, Jacobs JJ, et al. Results of unicompartmental knee arthroplasty at a minimum of ten years of follow-up. *J Bone Joint Surg Am*. 2005;87(5):999-1006.
3. Mariani EM, Bourne MH, Jackson RT, Jackson ST, Jones P. Early failure of unicompartmental knee arthroplasty. *J Arthroplasty*. 2007;22(6 suppl 2):81-84.
4. Furnes O, Espehaug B, Lie SA, Vollset SE, Engesaeter LB, Havelin LI. Failure mechanisms after unicompartmental and tricompartmental primary knee replacement with cement. *J Bone Joint Surg Am*. 2007;89(3):519-525.
5. Collier MB, Eickmann TH, Sukezaki F, McAuley JP, Engh GA. Patient, implant, and alignment factors associated with revision of medial compartment unicondylar arthroplasty. *J Arthroplasty*. 2006;21(6 suppl 2):108-115.
6. Herzog R, Morscher E. Failures of knee joint prostheses. An analysis of knee prostheses and component revisions, 1980–1987 [in German]. *Orthopade*. 1991;20(3):221-226.
7. Sandborn PM, Cook SD, Kester MA, Haddad RJ Jr. Fatigue failure of the femoral component of a unicompartmental knee. *Clin Orthop.* 1987;(222):249-254.
8. Assor M, Aubaniac JM. Influence of rotatory malposition of femoral implant in failure of unicompartmental medial knee prosthesis [in French]. *Rev Chir Orthop Reparatrice Appar Mot*. 2006;92(5):473-484.
9. Hernigou P, Deschamps G. Posterior slope of the tibial implant and the outcome of unicompartmental knee arthroplasty. *J Bone Joint Surg Am*. 2004;86(3):506-511.
10. Sawatari T, Tsumura H, Iesaka K, Furushiro Y, Torisu T. Three-dimensional finite element analysis of unicompartmental knee arthroplasty—the influence of tibial component inclination. *J Orthop Res*. 2005;23(3):549-554.
11. Jenny JY, Ciobanu E, Boeri C. The rationale for navigated minimally invasive unicompartmental knee replacement. *Clin Orthop*. 2007;(463):58-62.
12. Keene G, Simpson D, Kalairajah Y. Limb alignment in computer-assisted minimally-invasive unicompartmental knee replacement. *J Bone Joint Surg Br*. 2006;88(1):44-48.
13. Cobb J, Henckel J, Gomes P, et al. Hands-on robotic unicompartmental knee replacement: a prospective, randomised controlled study of the Acrobot system. *J Bone Joint Surg Br*. 2006;88(2):188-197.
14. Rodriguez F, Harris S, Jakopec M, et al. Robotic clinical trials of uni-condylar arthroplasty. *Int J Med Robot*. 2005;1(4):20-28.
15. Hernigou P, Deschamps G. Alignment influences wear in the knee after medial unicompartmental arthroplasty. *Clin Orthop*. 2004;(423):161-165.