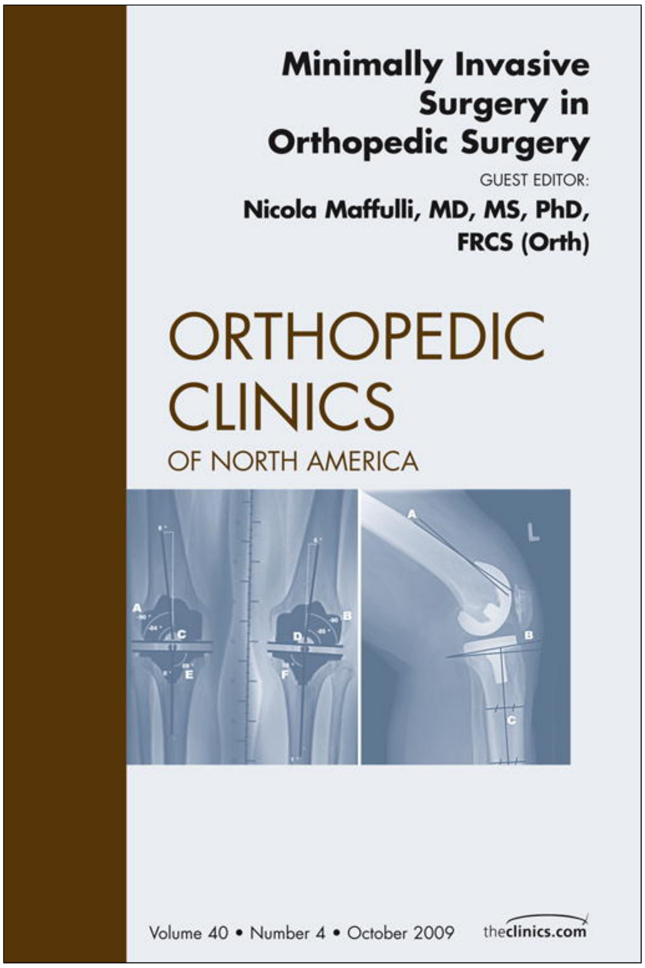
Minimally Invasive Surgery in Orthopedic Surgery
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Minimally Invasive Computer-Navigated Total Knee Arthroplasty

Nicola Biasca, MD[a,*], Thomas-Oliver Schneider, MD[b], Matthias Bungartz, MD[a]

KEYWORDS

- Computer-assisted navigated surgery
- Total knee arthroplasty • Malalignment • Malrotation
- Minimally invasive surgery

Total knee arthroplasty (TKA) is a highly successful procedure, with long-term follow-up studies reporting clinical success rates of 72% to 100%, as evaluated by pain reduction, functional improvement, and overall patient satisfaction at 10 to 20 years' follow-up.[1–5] Although TKA is generally successful, and despite the advances in the surgical techniques, instrumentation, and implant designs, between 5% and 8% of all patients develop complications such as anterior knee pain, loosening, instability, malpositioning, infection, or fractures.[6–8] The success of TKA depends on several factors, including patient selection, pre-operative deformity, appropriate implant design, correct surgical technique, soft tissue balancing, and alignment of the limb. Correct alignment of implanted components is considered one important factor that is under the surgeon's control at surgery. There is a definite relationship between the accuracy of implant positioning and longevity.[9–22] The most common cause of revision TKA is error in surgical technique: small changes in component positioning can lead to significant changes in post-operative performance.[23] Imperfections in the axial alignment of the femoral and tibial components, imperfect rotational alignment, improper ligament balancing, and incorrect joint-line restoration can lead to soft tissue imbalance and an inability to re-establish optimal kinematics and the overall biomechanics of the joint, with persistent anterior knee pain, patellar maltracking, varus/valgus instability, or limitation of movement.[9–14,23]

To address the problem of correct alignment, various mechanical alignment guides are used to improve the precision of implant positioning, but technical errors in surgical alignment still occur. Surgical navigation systems help reduce errors in component alignment during TKA. Although knee navigation systems are not yet universally accepted, several investigators have demonstrated with conventional radiography and CT that TKA implanted using computer-assisted navigation has more accurate component alignment than TKA implanted conventionally.[9,23–30]

Patient demand, potential health care savings, and the development of new instrumentation and techniques have led to rapid advances in less invasive surgical approaches. Minimally invasive surgical (MIS) approaches have been used with success in numerous types of surgical procedures, both arthroscopic and open. The introduction of MIS approaches for TKA has been driven partially by the use of small incisions and minimal soft tissue approaches in the performance of unicompartmental knee arthroplasty.[31,32] Motivating factors for patients include a possible reduction in duration of hospitalization and costs as well as concerns about post-operative pain, prolonged and

[a] Clinics of Orthopedic Surgery, Sports Medicine and Trauma Surgery, Department of Surgery, Spital Oberengadin, CH-7503, Samedan (St. Moritz), Switzerland
[b] Department of Orthopaedics, Hirslanden Clinic Permanence, CH-3018, Bern, Switzerland
* Corresponding author.
E-mail addresses: Biasca@medicmotion.com (N. Biasca); http://www.orthopaedie-samedan.ch

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arduous rehabilitation, and less-than-ideal functional outcomes associated with conventional TKA. Minimally invasive knee arthroplasty techniques (MIS TKA) also have been marketed intensively by the orthopedic implant industry. There is, however, concern about loss of accuracy in implant placement and increased complications related to skin slough and infection when a minimally invasive approach is used.[33,34]

Proponents of MIS TKA report that, compared with patients undergoing conventional TKA, patients undergoing MIS TKA experience decreased blood loss, shortened hospital stay, less need for pain-control medications, and faster recovery of knee range of motion, all without compromise of accuracy or short-term outcome.[35–37] Critics believe that the disadvantages include reduced operative visualization, a steep learning curve, an increased risk of complications, excessive skin trauma, and compromised implant fixation and alignment. Some surgeons have expressed concerns about the use of MIS TKA and the safety of operations performed "through a keyhole" and argue that at present there is no credible evidence that smaller incisions significantly benefit the patient receiving MIS TKA. Also, because of the steep learning curve, MIS TKA should not be performed unless the surgeon has a high-volume arthroplasty practice.[38,39] Although several recent studies demonstrate improved early clinical outcomes with the use of minimally invasive approaches, surgeons still are cautious about embracing MIS approaches, preferring a standard technique that provides consistently good clinical outcomes.[35,37,40–42] Furthermore, two recent studies reported that good alignment of TKA correlates with better clinical function, improved quality of life, quicker rehabilitation, and earlier hospital discharge.[43,44]

Here the author describes his technique of minimally invasive computer-navigated total knee arthroplasty (MIS CN-TKA) and his experience comparing two groups of patients treated with conventional computer-navigated total knee arthroplasty (CN-TKA) and MIS CN-TKA.

INDICATIONS AND CONTRAINDICATIONS FOR MINIMALLY INVASIVE COMPUTER-NAVIGATED TOTAL KNEE ARTHROPLASTY

Indications for MIS CN-TKA are similar to indications for conventional TKA: failure of nonoperative management of knee pain, loss of motion, and deformity and limitation of function resulting from arthritis.

The contraindications for MIS CN-TKA are not yet well defined; they may include patients who have active infections, neurologic deficits, malignancies, a stiff or arthrodesed hip or ankle, extreme adiposity, extreme knee deformities, severe bone or soft tissue trauma, severe bone destruction after rheumatoid arthritis, severe contracture or reduced of range of motion, severe osteoporosis, risk factors for wound healing complications, and revision surgery of a previous implanted TKA.

SURGICAL APPROACHES FOR MINIMALLY INVASIVE TOTAL KNEE ARTHROPLASTY

The clinical definition and criteria for MIS have not been firmly established. Different parameters have been used to define MIS, including length of incision, location of incision, muscle-sparing approaches, reduced in-patient hospital stay, and rapid muscle recovery. The most definitive characteristics of MIS, which include reduced soft tissue trauma and improved post-operative functional recovery, often are overlooked.

MIS TKA uses skin incisions 8 to 12 cm long in the smallest and largest patients, respectively, compared with incision lengths of up to 25 cm in conventional approaches. The length of the skin incision is adjusted according to the surgeon's experience, the size of the implant needed, and the elasticity of the soft tissue. The length of the skin incision has only cosmetic implications and should not affect recovery. Insufficient tension on the skin may jeopardize wound healing and cause necrosis or lacerations. Although a small incision seems desirable to many patients, a small incision is not the reason these operations may have better outcomes. The minimization of soft tissue dissection and disruption, lack of patella eversion, and in situ bone-cutting techniques to minimize articular dislocation are clearly more important in producing improved outcomes. Therefore, the skin incision should not compromise the integrity of the wound or the ability to perform proper surgery with the computer-navigation technique.

The minimal incision technique can be viewed as part of a continuum in the transition from classic, more extensive exposures to the true quadriceps-sparing MIS TKA. The intention is to reduce surgical dissection without compromising the procedure. Although it often is suggested that one or another "minimally invasive" approach compromises the extensor mechanism, in truth, each of these approaches preserves the extensor mechanism to a greater degree than a standard approach.

Several approaches have been described for MIS TKA.[33,35,40,45–48] One minimally invasive technique, the minimally invasive medial parapatellar approach, simply shortens the standard quadriceps incision through a 10- to 14-cm skin incision along the anterior midline, extending from the superior pole of the patella to the superior aspect of the tubercle. The arthrotomy extends 2 to 4 cm into the quadriceps tendon proximal to the superior pole of the patella.[40,45] This approach generally enables lateral patellar subluxation, without eversion, and in many patients the exposure of critical landmarks is unimpeded. If necessary, the arthrotomy can be extended easily to a more traditional approach by gradually lengthening the incision into the quadriceps tendon.

Two alternative approaches are the modified minimally invasive subvastus approach introduced by Hofmann and colleagues[46] and the minimally invasive midvastus approach introduced by Engh and colleagues,[47] both of which reduce post-operative pain, preserve vascularity of the patella, improve patellar tracking, enhance return of quadriceps strength, decrease blood loss, and accelerate rehabilitation, even through a standard incision. With the minimally invasive subvastus approach, the capsular incision is performed entirely distal to the patellar attachment of the quadriceps mechanism. The extensor mechanism is visualized, and the medial capsular incision is made from the border of the middle of the patella along the medial side of the patellar tendon and distal to the tibial tubercle. The attachment of the muscle to the quadriceps tendon and the upper patellar bone is left intact. After a synovial release of the suprapatellar pouch is performed, and the vastus medialis obliquus (VMO) is released from the intramuscular septum, the patella can be everted or subluxed laterally. The concern with this approach is the possibility of injuring the descending genicular artery and its branches, the saphenous nerve, and intramuscular septal arteries as well as the femoral vessel as they pass through the adductor hiatus.[46] The minimally invasive midvastus approach, an excellent alternative, evolved as a compromise between the exposure of medial parapatellar approach and the benefits of the subvastus approach involving the extensor mechanism.[47] The minimally invasive midvastus approach is performed through a standard anterior midline skin incision from 3 cm above the patella and 3 cm distal to the joint line, and a medial subfascial flap is developed to expose the broad insertion of the vastus medialis (**Fig. 1**).

Extension of the intermuscular interval is facilitated by blunt finger dissection or controlled release by electrocautery. To allow full eversion of the patella, the capsular folds of the suprapatellar pouch must be release proximal to the patella.

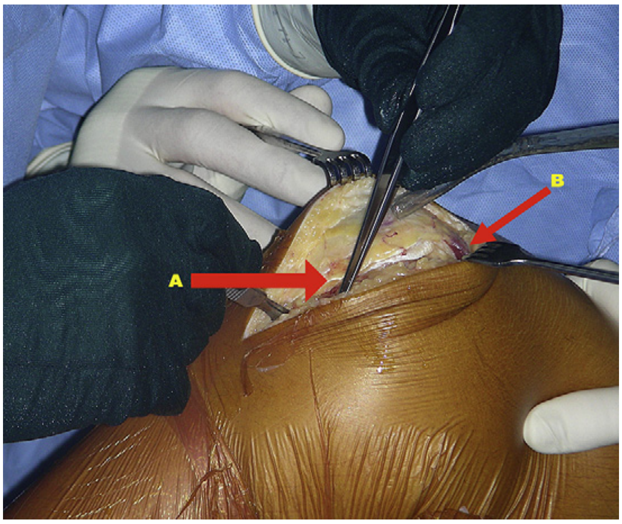

Fig. 1. The minimally invasive MIS midvastus approach. After the incision of the skin and subcutaneous tissues, the medial arthrotomy (A) is performed with an incision of the retinaculum patellae (*thick red arrow*) along the medial side of the patella to the inferior aspect of the wound. With the knee in flexion, the full thickness of the vastus medialis muscle (B) is divided in line with its muscle fibers, starting at the superomedial corner of the patella and extending proximally for about 4 to 5 cm. The amount of release is titrated later with gradual and purposeful patellar eversion and knee flexion.

The distal capsular portion of this approach involves incising the medial retinaculum and capsule along the patella and patellar tendon. This approach allows adequate exposure of the joint and improved post-operative recovery and pain relief. in an attempt to minimize soft tissue damage and preserve quadriceps muscle function, Seyler and colleagues[48] described a new approach, the minimally invasive direct lateral approach. Instruments and implants were not customized for this approach, however, and a significant rate of early complications may limit the potential of this approach until further refinements increase clinical success and make this technique suitable for general use.

Although the approaches are well recognized, these techniques often are demanding and require appropriate technical tuition even for experienced knee surgeons. The most important aspects of minimally invasive TKA are related to the soft tissues. Therefore, a cadaver course is recommended to practice the techniques of maximizing visualization using flexion, midflexion, and extension windows and of using the space produced in this fashion after each bone resection. (Further information on the author and his colleagues' cadaver course can be found at www.orthopaedie-samedan.ch).

COMPUTER-ASSISTED ORTHOPEDIC SURGERY

The principle of computer-assisted orthopedic surgery is simple. A digital image serves as a map for each particular step of the procedure. This image guides the surgeon through the operation. Information from three sources can be used to establish the digital map. The first source of information is pre-operative imaging; anatomic information is collected before operation by a CT scan or MRI. The patient and the health care system are exposed to the inconvenience and cost of the CT or MRI. The second source of information is perioperative imaging, performed in the operating suite at the time of surgery. This imaging requires a specially modified fluoroscopy unit and entails the maneuvering of a relatively bulky and expensive apparatus during surgery. These two sources comprise the "image-based systems." The third information system is image free and relies on information acquired during surgery. This system allows the surgeon to quantify data, to have dynamic intraoperative feedback, and to obtain more reproducible results. A very important attribute of image-free navigation is its ability to provide instant feedback regarding in vivo kinematics of the joint. Alignment and ligament stability can be assessed with the trial components in place to ensure proper function. Furthermore, this system allows the measurement of any degree of flexion, the coronal deformity, alignment, stability, rotation, and translation. This characteristic of the navigation system provides the unique opportunity to assess in vivo kinematics of the knee during surgery and to implement beneficial changes such as refinements in soft tissue tensioning, rotational adjustment of the components, or changes in components selection.

The Stryker Leibinger Knee Navigation System (software version 3.0, Stryker-Leibinger GmbH & Co. KG, Freiburg, Germany) is an image-free navigation system that has been modified progressively since 1999 to translate the generated data more clearly for the surgeon. This system now is available in an active wireless personal computer–based guidance system, which is based on an imageless navigation method and thus does not require pre-operative CT or intraoperative fluoroscopy. It comprises a module for analyzing the alignment of the leg, the alignment of the resection planes, and thus the alignment of the prosthetic components. The system also quantifies the kinematics of the knee. Two hardware platforms are available: a laptop and a workstation version. Both are portable units consisting of a personal computer, an infrared camera system, a flat-screen monitor, and menu prompts. The operational aspect of the system occupies a spherical area with a radius of about 50 cm. The system is most accurate when located 1.5 m from the operating field. The working space of the system is a sphere 1.0 m in diameter, so the maximum working distance is 2.0 m. The system's software runs on a standard laptop (Dell Latitude, Dell Computer Corporation, Round Rock, Texas) using Microsoft Windows 2000 (Microsoft Corporation, Redmond, Washington). The wireless navigation instruments and the camera communicate via active battery-powered light-emitting diodes. The surgeon navigates the procedure via a menu on a flat screen using a specially developed pointer. The pointer allows the surgeon to maintain control of all software functions during the procedure and to access to various submenus without using foot pedals or touching the screen. The technology does not need a computer specialist at hand. The active wireless localizers, the trackers, are fixed on special pins, which are placed at two locations bi-cortically on the distal femur and proximal tibia. The tracker's "quick connect and release" design allows simple removal of the device while maintaining precise positioning. All trackers are placed in the usual surgical field. The infrared camera registers the absolute motion in the coordinate system, and the software calculates the relative motion of two adjacent trackers. (Further details about the Stryker Knee Navigation System are available at http://www.europe.stryker.com/.)

COMPUTER-ASSISTED TOTAL KNEE ARTHROPLASTY

After standard preparation and draping, the leg is exsanguinated in a routine fashion, and the tourniquet is inflated. The procedure is initiated by positioning two femoral pins through stab wounds along the iliotibial tract and a single tibial pin distal to the tibial tuberosity. Special antirotational fixation pins have been developed specifically for this purpose that are suitable for bi-cortical anchorage and for quick connection to the trackers. The joint kinematics can be monitored whether the joint capsule is open or not. To set up the Navigation Software Setup System, the patient's data are entered, and the pointer and trackers are initialized. The anatomic landmarks then are defined with the anatomic mapping following the information from the screen. The on-screen instructions guide the surgeon. The exact center of the femoral head is pinpointed by rotational calculation with a special algorithm of the customized software. Calibration involves moving the leg to obtain various hip positions. Then single-point digitalization with the pointer is used to mark the surgical epicondylar axis, the Whiteside line, the femoral and tibial centers, and the malleoli. An algorithm of the Stryker system calculates the center of the ankle by digitalizing the malleoli. The actual pathologic deformity is calculated from the data, and the pre-operative deformities present are shown. The mechanical axis of the limb and the transepicondylar axis of the femur, the morphology of the femoral condyles, the morphology of the tibial plateau, and the long axis of the tibia are all identified, and the image data are stored. The specific anatomic landmarks and vectors recorded on the femur are the surgical medial and lateral epicondyles, the center of the distal femoral condyles, and the trochlear groove (eg, the Whiteside line). The algorithms provided by the system to determine the axial rotation of the femur average the readings of the transepicondylar axis and the Whiteside line. Surface digitalization identifies the femoral condyles and tibial plateau to determine the exact level of resection and to prevent alteration of the joint line. The data collected are used to calculate the current clinical status by mathematical algorithms, and the deformities detected pre-operatively are imaged. Kinematic curves are generated based on the distance between the landmarks during maneuvers such as varus/valgus, rotational stress, or anteroposterior movement. After the multiple landmarks have been digitalized and after the initial kinematics curves and axis have been analyzed by moving the limb from maximal extension to maximal flexion, bone cuts are performed based on the information obtained from the navigation system.

SURGICAL TECHNIQUES

Operating Theater

No specific modifications to the operative setting are needed for the procedure. A standard operating-room table with two distal foot supports allows the knee to be flexed to 45° or 90°, because the surgeon will operate in flexion, midflexion, and extension surgical windows.

Instruments

MIS TKA must be performed with accurate instruments specially developed for the procedure. It is not possible to perform the operation with the traditional instruments developed for the open approach. The conventional instruments do not fit into the knee joint and do not allow visualization of the joint while the cuts and balancing are performed. The visual appearance is totally different and new. Surgeons must learn to interpret a completely new image of the knee joint while continuing to apply the basic principles that they have learned. The instruments are a critical part of this new technology and are essential for its success. New instruments that are roughly half the size of traditional instruments have been developed to facilitate MIS TKA. (Further details about the specially developed instruments are available online at http://www.europe.stryker.com/.)

Pre-operative Planning

Pre-operative assessment must include a thorough physical examination and proper plain radiographic studies. At the physical examination, the Pre-operative deformity, range of motion, and laxity of the joint at different knee position should be documented. The Pre-operative radiographs should document deformity and malalignment, osteophytes, bone defects, and loose bodies. The Pre-operative posterior slope of the tibial cut should be measured on the conventional lateral radiographs at 30° of knee flexion, to plan this slope on surgical setting.[16]

Anesthesia Technique

Anesthesia in MIS TKA should provide adequate pain relief and muscle relaxation during the procedure and minimize post-operative pain. For post-operative pain control, the author's patients receive first a single sciatic nerve block and then a continuous femoral nerve block.[49,50] Regional techniques are performed on conscious, only slightly premedicated patients (5–10 μg of sufentanyl administered intravenously shortly before starting the procedure), using a neurostimulation device (Stimuplex HNS 11, Braun Melsungen AG, Melsungen, Germany) and stimulating needles.

The single-shot sciatic nerve block

The sciatic nerve is the largest nerve in the body, measuring about 2 cm in thickness in its proximal portion. At this location, it actually is composed of the sciatic nerve and the posterior cutaneous nerve of the thigh. This double nerve contains contributions from the lumbar nerve roots 4 and 5 and the sacral nerve roots 1, 2, and 3.

The single-shot sciatic nerve block is performed using the classical Labat approach with the patient in the lateral position, exposing the affected side (**Fig. 2**).[49] The needle (Polymedic UPC G23, 150 mm; Polymedic, TeMe Na, Carrieres sur Seine, France) is advanced toward the sciatic nerve until foot movements can be elicited at a threshold of 0.4 mA, 0.1 msec. A total of 15 to 20 mL ropivacaine 0.75% (Naropin®) is administered. This dose usually provides satisfactory analgesia for

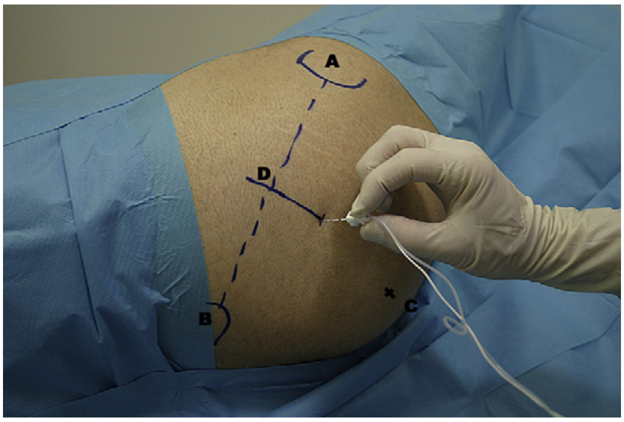

Fig. 2. The single sciatic nerve block is done following the technique of Labat:[49] The patient first is placed in the lateral position with the side to be blocked up. While the lower leg is kept straight, the thigh is flexed at the knee so that the ankle is brought over the knee of the other leg. The important bony landmarks to block the sciatic nerve via the two posterior approaches are the greater trochanter (A), the posterior superior iliac spine (B), and the ischial tuberosity (C). A line is drawn between the greater trochanter (A) and the posterior superior iliac spine (B). The line lies approximately over the upper border of the piriformis muscle. From the midpoint of this line (D) and at right angles to it, a second line is drawn passing over the buttock. The point of injection is 3 to 5 cm along this perpendicular line. It can be identified more precisely by drawing a third line between the greater trochanter and sacral hiatus; the point of injection is the intersection of this third line with the second, perpendicular line.

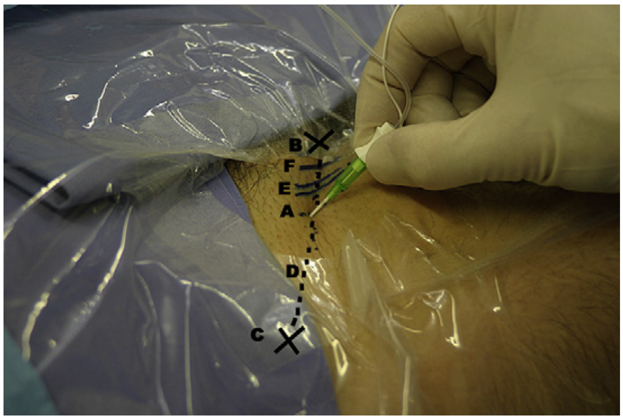

Fig. 3. The femoral nerve block is performed with the patient supine following the technique of Winnie.[50] The important bony landmarks for blocking the femoral nerve (A) are the pubic tubercle (B), the anterior superior iliac spine (C), the inguinal ligament (D), the lateral border of the femoral artery (E), and the femoral vein (F) at the inguinal crease. For the femoral nerve (A), the point of injection lies just below (distal to) the inguinal ligament (D). Palpate both the anterior superior iliac spine (C) and the pubic tubercle (B). The line between these two points overlies the inguinal ligament (D). It often is helpful to draw lines on the skin. The femoral artery (E) should lie at the midpoint of the inguinal ligament, and it is necessary to locate the artery by palpating the pulse at this point. The injection site is 1 cm lateral to lateral edge of the pulse of the femoral artery and 1 to 2 cm below (distal to) the line of the inguinal ligament.

more than 24 hours. Alternatively, especially in immobile patients, the anterior[51] or lateral[52] approach for IB (sciatic block modified according to Meier) can be used.[53,54]

The continuous femoral nerve block

The femoral nerve receives contributions from the second, third, and fourth lumbar nerves. It is derived from the lumbar plexus and in fact lies within the same fascial envelope as the lumbar plexus. Therefore a single injection distally may be utilized to block most of the nerves originating in the lumbar plexus, because local anesthetic can pread proximally within this plane.

The femoral nerve block is performed with the patient in the supine position (**Fig. 3**). The catheter is placed using the classic paravascular Winnie approach.[50] The needle (Borgeat C 70T, Polymedic) is advanced until contractions of the quadriceps femoris muscle, at a threshold of 0.4 mA, 0.1 msec, indicate accurate positioning of the needle tip in the immediate proximity of the femoral nerve. After negative aspiration, 5–10 mL of NaCl 0.9% is injected. The needle is removed, and the catheter advanced 5 to 10 cm through the plastic cannula. After subcutaneous tunneling (5 cm) and application of a bacterial filter, 5–10 mL of lidocaine 1% is injected.

Because of the inconsistent blockade of the obturator nerve with the previously described blocks, the operation is performed with an additional lumbar spinal anesthesia (hyperbaric bupivacaine 0.5%, 2.5–3 mL) administered using a Reganesth Pencil Point G27 needle (Reganesth, Villingen, Germany) or general anesthesia (ie, propofol, remifentanil).

Immediately post-operatively, the femoral catheter is connected to a patient-controlled analgesia pump delivering ropivacaine 0.2%, usually set at a basic rate of 6 mL/h, with a 4-mL bolus function and a 30-minute lockout time. The setting then is adjusted according to the individual patient's pain scores and symptoms (particularly motor blockade) during daily ward rounds. The femoral catheter usually is left in place for 48 to 72 hours, depending on the individual patient's requirement.

Surgical Procedure

The patient is placed supine on a standard operating table. A tourniquet is applied after exsanguination of the limb, and standard skin preparation and draping are undertaken. Two fixed leg holders on the operating table allow flexion and extension of the lower limb for exposure. Flexing the knee exposes the posterior structures of the knee, and extending the knee exposes the anterior structures of the knee.

Navigation trackers pin position

The procedure is initiated by positioning one tracker on the distal femur and one tracker on the proximal tibia within the surgical access zone. These trackers are fixed rigidly to the bone so that their position in relation to the anatomically selected points remains constant, and any movement of the bone and its associated tracker position is recorded. The femoral tracker is fixed rigidly to the femur with the Ortholock, a femoral tracker fixing device (Stryker-Leibinger, Freiburg, Germany) with two bi-cortical predrilled pins (3 mm in diameter and 150 mm long) through stab wounds along the iliotibial tract 10 cm proximal to the patellar pole in an anterolateral to posteromedial direction. The tibial tracker is fixed with a special antirotational fixation pin through a small stab wound into the proximal tibia 15 cm distal to the tibial tuberosity. The information regarding the position of the trackers, the attached bone, and the instruments is analyzed by the computer, which determines the real-time position of the leg within a three-dimensional coordinate system. In the most recent modification of the system, only two trackers, one fixed to the distal femur and one fixed to the proximal tibia, are necessary.

Surgical approach

The author's preferred approach is the minimally invasive midvastus approach, with a length of approximately 8 cm in extension and 10 cm in flexion. The skin and underlying subcutaneous tissue are incised to expose the underlying retinaculum of the knee. At the superior end of the wound the fibers of the VMO are seen to insert into the medial aspect of the patella. A 2-cm stab wound is made in the VMO fibers at the edge of the patella in the 10 o'clock or 2 o'clock position, depending on the operative side. The incision then is continued along the medial side of the patella to the inferior aspect of the wound (see **Fig. 1**). With the leg in extension and two soft tissue retractors appropriately placed, the suprapatellar pouch is visible. The anterior capsule, a fine white fibrous layer, is dissected with Meztenbaum scissors and is divided longitudinally. The fat and synovial tissue over the anterior surface of the distal femur are removed, and any plical bands attaching the medial capsular layer to the medial side of the femur are divided. The same process is accomplished on the lateral aspect. With the knee in extension, the patella is osteotomized freehand to a bone thickness of 12 mm for later resurfacing. This process allows further visualization of the lateral gutter (**Fig. 4**).

Through the distal medial arthrotomy wound, the anterior horn of the medial meniscus is excised. Care is taken to limit the excision of the fat pad beneath the patella tendon to avoid contracture of the patellar tendon. An interval is produced on the medial aspect releasing the anteromedial knee capsule/retinaculum from the anterior surface of the tibia and allowing visualization of the medial aspect of the knee. With the knee in mid-flexion/extension, a Langenbeck retractor is placed under the patellar tendon close to its insertion in the tibia. The surgeon now can visualize the anterolateral surface of the tibia, and the anterior horn of the lateral meniscus can be removed under direct vision.

Data analysis and bone resection

The digitizing pointer then is used to mark the key anatomic landmarks. The anatomic landmarks of the femur condyle must be prepared very precisely intraoperatively (**Figs. 5** and **6**).

After digitalization of the multiple landmarks, the surgeon can reproduce the correct joint kinematics with the Knee Navigation System (**Fig. 7**).

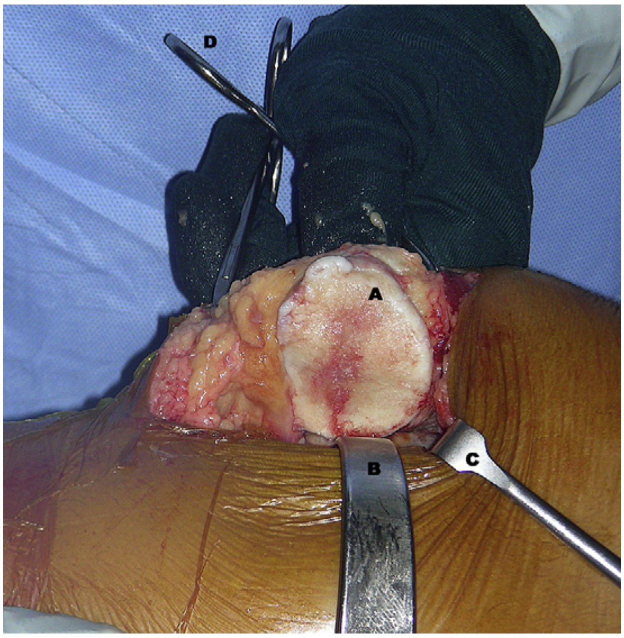

Fig. 4. With the knee in extension, the patella (A) is osteotomized freehand with the saw. The lateral femoral condyle is protected with a double femoral retractor (B), and the vastus medialis muscle is protected by a small Langenbeck retractor (C). Care must be taken not to injure the patellar and quadricepital tendons, which are held with two Backhaus clamps (D).

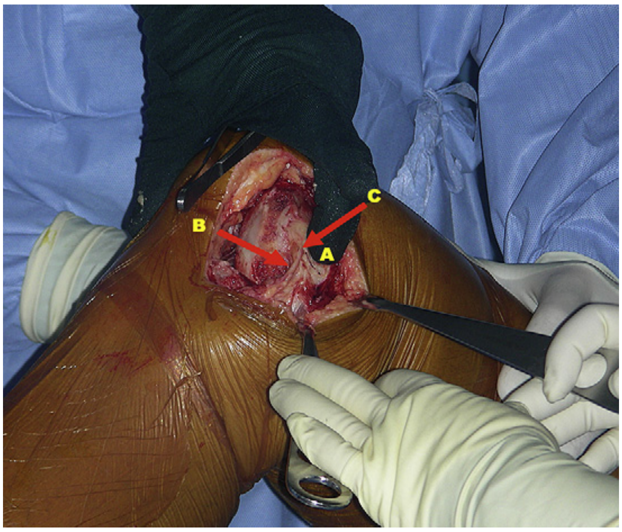

Fig. 5. Through the medial incision the surgeon prepares the medial epicondyle of the femur (A). To digitalize the medial epicondyle clearly with the pointer (B), the surgeon identifies the attachment of the superficial fibers of the medial collateral ligament attaching to the crescent-shaped prominence on the bony ridge of the medial epicondyle (C) and of the deep fibers of the medial collateral ligament in the sulcus.

After analyzing the kinematics curves and axis, bone cuts are performed using the information obtained from the navigation system. The author usually starts with the tibial cut. The proximal tibial cut is made in one step, controlling the posterior slope, varus/valgus, and depth. The posterior slope of the tibial cut is aimed to match the original posterior slope of the tibial plateau.[16] The cutting guide with the resection plane probe is placed in the wound and the medial soft tissue envelope. Using the freehand technique, the surgeon adjusts the position of the probe according to the image and data shown on the computer. The guide is held using a tripod grip, and the visual movements of the guide can be monitored in real time on the screen (**Fig. 8**A, B).

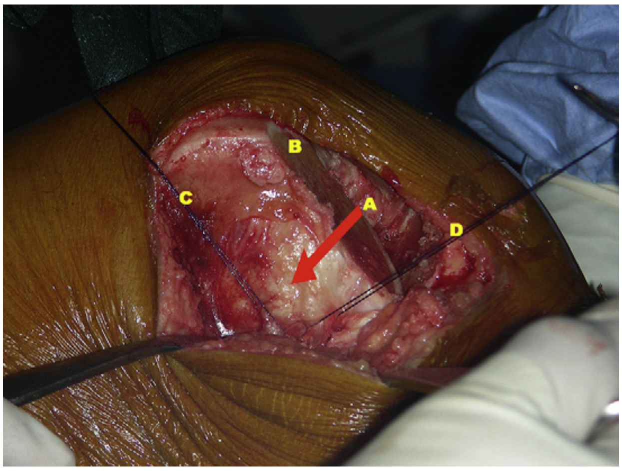

Fig. 6. During the initial anatomic landmark registration, the lateral epicondyle of the femur (A) can be palpated only approximately. After resection of the distal femur (see **Fig. 11**), (B), the lateral epicondyle can be remapped by palpating the smaller and less protuberant prominence of the lateral epicondyle (A), which corresponds to the attachment of the fibular collateral ligament of the knee (C). On the lateral surface of the lateral femoral condyle, the surgeon can visualize the origin of the popliteus muscle (D), anterior and inferior to the lateral epicondyle, which courses under the lateral collateral ligament and descend into the popliteus hiatus.

Once the cutting guide is set in the final position, the block is secured into place with three pins, and the proximal tibial resection is performed with the saw blade (**Fig. 9**A). After the resected part of the tibia plateau is removed, the resection plane probe is used to verify the accuracy of the cut and to record the final cut on the screen (**Fig. 9**B).

The femoral distal cuts then are made as a two-step process, using the two femoral cutting blocks, the cutting guide, the femoral alignment guide, and the resection plane probe. The author begins with the distal femoral resection, which requires control of flexion/extension, varus/valgus, and depth of bone resection (**Fig. 10**).

After the distal femoral portion has been resected, the rotational landmarks of the femur are reviewed and, if necessary, remapped using the pointer. The rotational alignment subsequently is established with the femoral alignment guide and resection plane probe. The femoral component rotation is aimed to be 0° in relation to the special algorithm of surgical transepicondylar axis and the Whiteside line as provided by the computer software. With the computer-assisted navigation it possible to avoid an anterior femoral notching during the preparation of the distal femur and the femoral component can be aligned in the requested flexion (**Fig. 11**A–D).

Care is taken to release any flexion contracture, to remove all the posterior femoral osteophytes, and to align the femoral component in 1° of flexion, with the navigation system in the sagittal plane. The author then measures the femoral size with the femoral sizing guide, and finishes the preparation of the trochlea of the femur with trochlea resection guide. The femoral component then is inserted and, once it is seated correctly, the fixation lugholes are drilled (**Fig. 12**).

Subsequently, the tibial bone resection is finalized. The appropriately sized tibial baseplate is inserted, and the tibial component rotation is determined through self-adjustment by flexing and extending the knee with the trial femoral component implanted. The tibial component

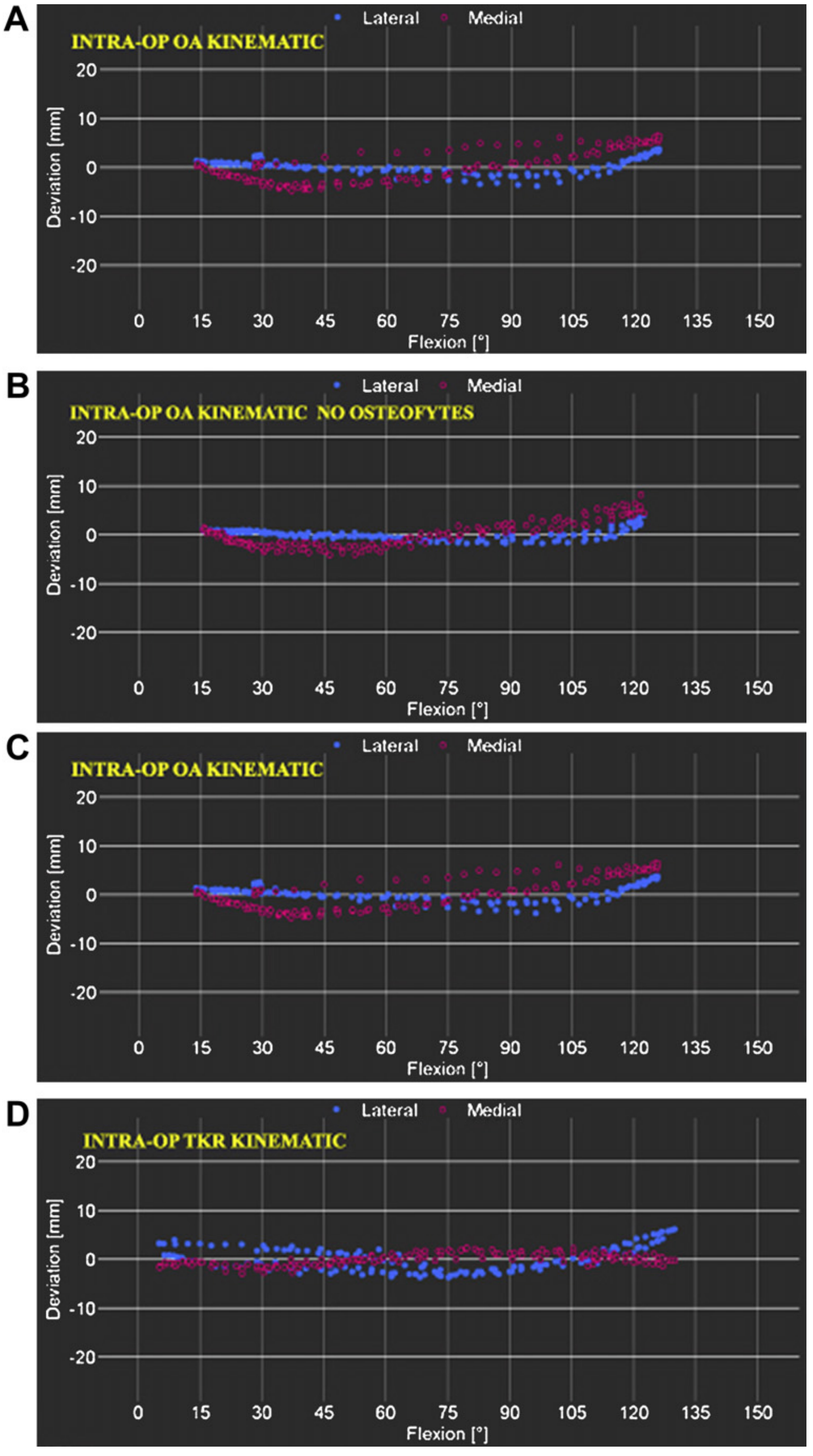

Fig. 7. (*A–D*) Progressive release of soft tissue. After the resection of the osteophytes, the surgeon can restore the correct joint kinematics with a progressive appropriate release of the soft tissue using initial kinematics quantified by the navigation technique to achieve parallel lengthening of the collateral ligaments through the entire range of motion.

rotation then is noted, and later the component is implanted with the desired rotation (**Fig. 13**).[55,56]

Trial component insertion

Before the trial components are inserted, the tibial and femoral bone cuts are verified with a small resection plane probe that is applied directly on the affected bone. Each bone cut performed is recorded and stored by the system and can be used for post-operative evaluation. After the tibial, femoral, and soft tissue preparation is complete and the trial components have been inserted, the

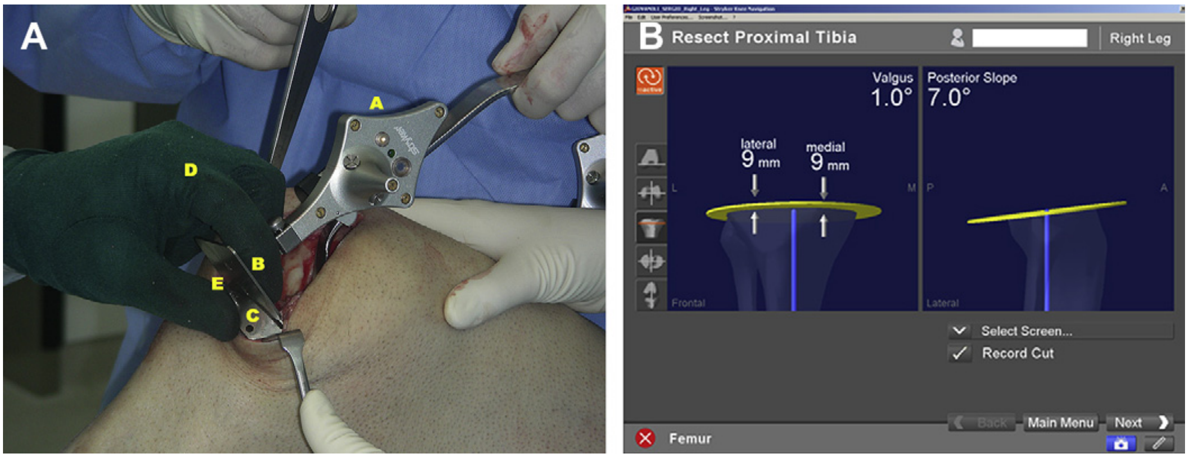

Fig. 8. (*A*) The proximal tibial resection requires the surgeon to position the MIS cutting guide in relation to the three axes of freedom controlling the varus/valgus, the depth, and the posterior slope, using a freehand technique. The universal tracker (A) is attached to the resection plane probe (B), which in turn is placed into the captured slot of the cutting guide (C). The surgeon holds the cutting guide/tracker construct using a "tripod grip" (D). The block is secured in place with three pins (E). (*B*) The cutting guide/tracker construct is now an active tool whose virtual position (ie, the varus/valgus angle, the slope angel and the depth) can be monitored on the computer navigation screen.

correct position of the trial components is checked with a small resection plane probe. Subsequently, the patella preparation is finished, and patellar tracking is checked with the trial implants in place.

Soft tissue assessment of trial components

After the insertion of the components, the limb alignment and the soft tissue balancing are assessed on the screen with the intraoperative kinematics by moving the limb from extension to deep flexion under neutral, varus, and valgus stress through the heel of the foot, maintaining the limb in the same rotation (**Fig. 14**).

Using this information, the surgeon can plan any changes in the polyethylene insert and soft tissue release before repeating the assessment. In this way the surgeon obtains constant feedback during the process of balancing the knee (**Fig. 15**).

Definitive component Insertion

All patients receive a posterior-stabilized Scorpio knee total prosthesis (Stryker Howmedica

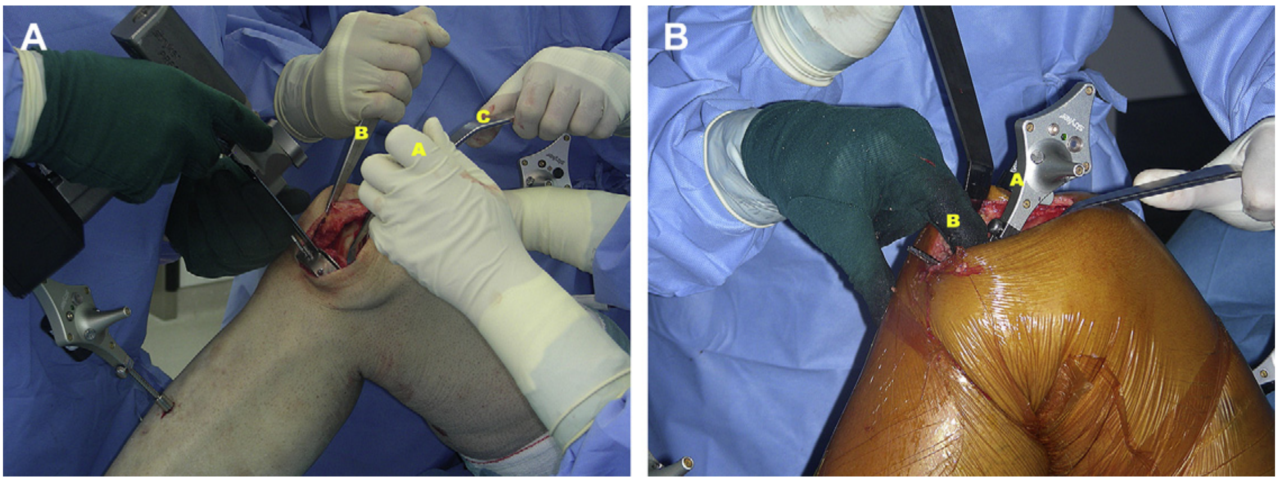

Fig. 9. (*A*) Proximal tibial resection with the saw blade. With the knee flexed, two retractors protect the soft tissue on the medial (A) and lateral side (B), and a giraffe retractor (C) is placed posteriorly to deliver the tibia lightly forward. Two retractors are necessary to protect important anatomic tissue: at the medial margin of the tibia plateau (A) to protect the medial collateral ligament and at the posterolateral corner of the tibia (B) to protect the popliteus tendon and the lateral genicular vessels. (*B*) After every bony resection, the universal tracker with the resection plane probe (A) can be placed flush on the cut surface to verify the accuracy of the cut (B). The surgeon can correct the cut by cutting freehand with the saw blade. Finally, the surgeon can record the tibial cut on the screen.

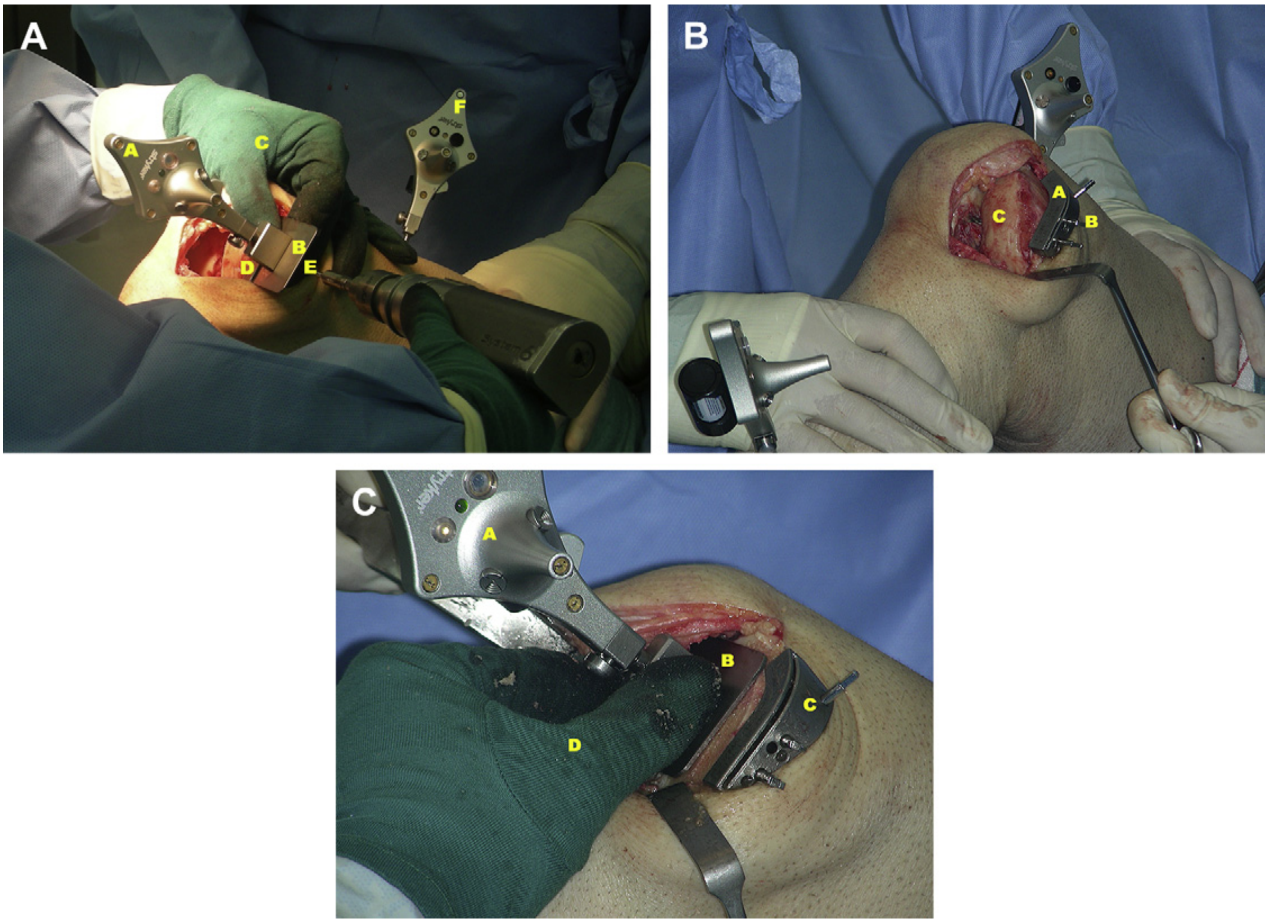

Fig. 10. (*A*) Distal femoral resection. The same cutting guide is used with the universal tracker (A) with the resection plane probe (B) placed in the captured slot (C). A similar freehand technique of cutting guide (D) placement is also used for the distal femoral resection. The block is pinned into place with three pins (E). The femoral tracker (F) is visible in this picture. (*B*) The cutting block (A) is fixed with three pins (B), and the surgeon uses a saw blade to effect the desired distal femoral resection (C). In this picture, the femoral and tibial trackers are also visable. (*C*) After the bony resection, the universal tracker (A) with the resection plane probe (B) can be used to verify the accuracy of the cut, to recorrect the resection if necessary, and finally to record the distal femoral cut on the screen. In the picture, the cutting block (C) is visible, and the freehand technique (D) of holding the universal tracker with the resection plane probe is demonstrated.

Osteonics, Freiburg, Germany). All femoral and tibial components are cemented with the Stryker Compact Vacuum Cement Mixing System. With the knee in deep flexion, two curved retractors are placed into the medial and lateral tibial plateau, and one retractor is placed posteriorly to deliver the tibia forward. The Scorpio tibial baseplate then is inserted into the keel cut and is cemented into position while its location is controlled with the resection plane probe (**Fig. 16**).

Any excess bone cement is removed under direct vision. In the same way, the Scorpio femoral component is cemented into the femur (**Fig. 17**), a trial polyethylene inlay is inserted, and thereafter the patellar component is embedded with cement (**Fig. 18**).

After the cement is fully polymerized, the tourniquet is released, and accurate hemostasis is performed. At this point it still is possible to assess the joint and soft tissue balance using trial polyethylene inlays of different sizes and to show the final kinematics analysis on screen, before the surgeon makes the final choice of insert size.

Closure

The joint is irrigated thoroughly, and a drain is inserted. The arthrotomy is closed with interrupted Vicryl 2-0 absorbable sutures with the knee at 90° of flexion. The subcutaneous layer is closed with Vicryl 2-0 sutures, and the skin is closed with Ethycrin 4-0 sutures (**Fig. 19**).

Subsequently, the final kinematics and outcome are documented, recorded, and compared with the initial kinematics data to assess the success of any correction (**Fig. 20**A, B). The data can be printed out and kept in the patient's record.

Postoperative Treatment

Peri- and post-operative pain treatment includes epidural anesthetic for 2 to 4 days and oral

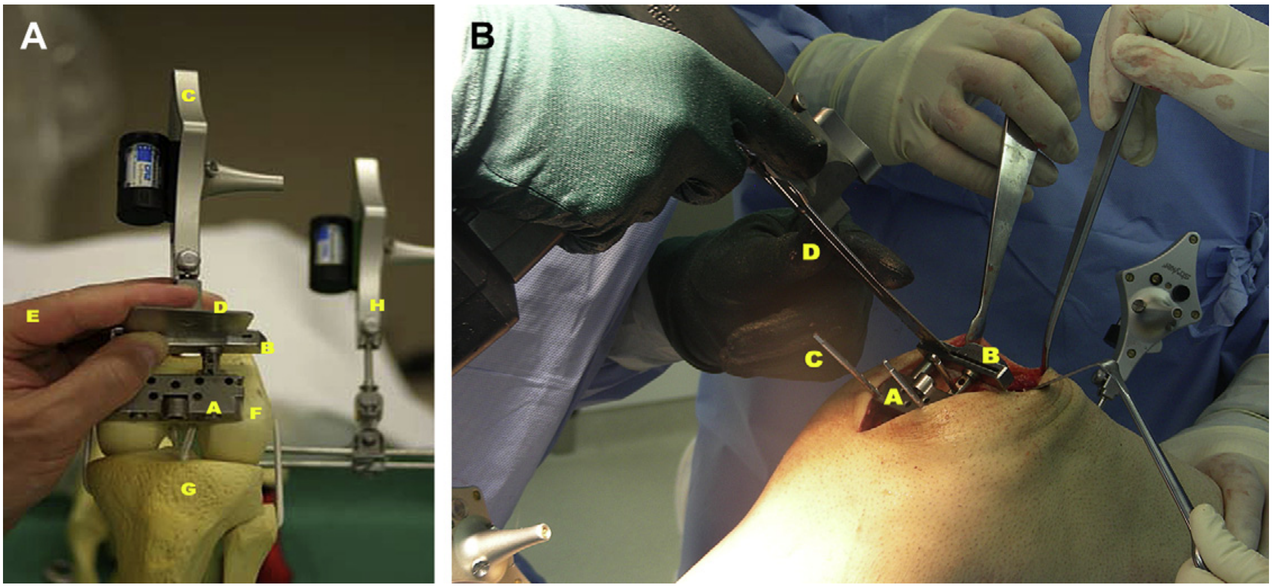

Fig. 11. (*A*) This picture shows on a model the adjustment of the femoral rotation with the base block (A), the anterior skim cutting guide (B), and the universal tracker (C) with the resection plane probe (D), which are placed with the freehand technique (E) into the desired rotation of the femoral component (F) and then pinned in place. The anterior skim cutting guide (B) is then raised flush with the anterior cortex of the distal femur avoiding dorsal notching of the distal femur cortex. The distal dorsal femoral cut can be performed with the saw blade. The proximal tibia (G) and the femoral tracker (H) are visible in the picture.

Fig. 11. (*B*) This picture shows the intra-operative view with the minimally invasive approach for the adjustment of the femoral component rotation. The femoral alignment guide with the base block (A) and the anterior skim cutting guide (B) have been secured with three pins (C). The distal dorsal femoral cut can be performed with the saw blade (D).

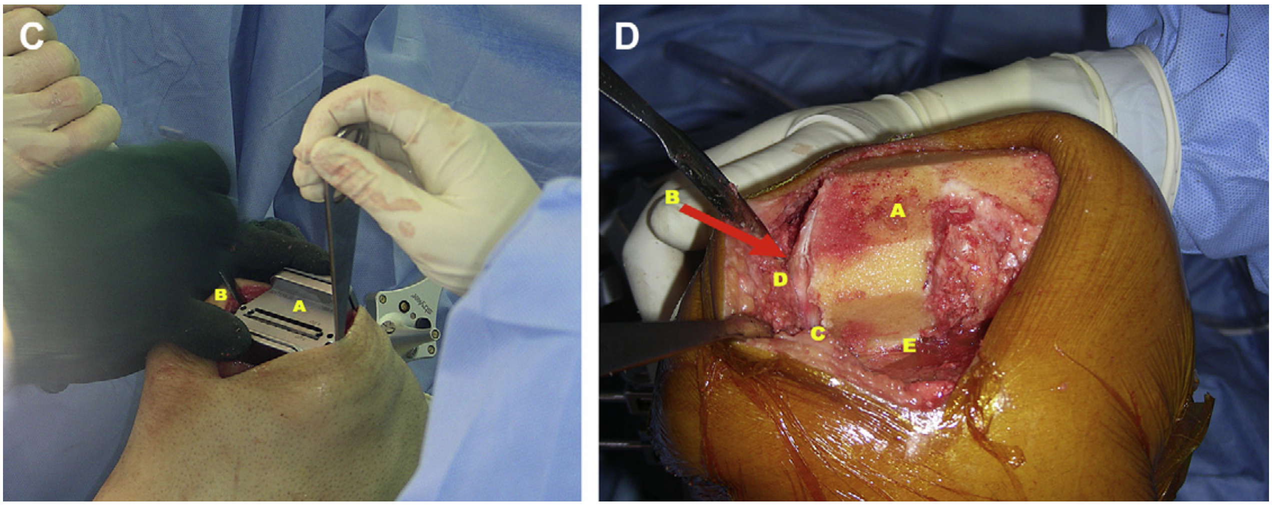

Fig. 11. (*C*) This picture shows the intra-operative view with the minimally invasive approach with the femoral resection guide in situs (A). After the distal dorsal femoral cut has been performed and the corrected femoral component rotation has been checked with the resection plane probe, the femoral component size can be selected. The appropriate size of the femoral resection guide (A) is chosen, placed onto the distal femoral cut surface, and secured with four pins (B, here with only one pin for this picture). The distal femoral cut can be finished with the saw blade.

Fig. 11. (*D*) This picture shows the intra-operative after performing all the distal femoral cuts. The resection level of each surface of the distal femur (A) can be measured with the resection plane probe and checked for accuracy. The thick red arrow (B) points to the lateral epicondyle. Two retractors are protecting the popliteus tendon (C), the lateral collateral ligament (D), and the soft tissue structures. The postero-lateral femur condyles (E) can now be cut with a curved osteotome, and the posterior capsule released and excised. The same step will be done for the medial femur condyle in the same way.

Fig. 12. Insertion of the femoral component. With the lateral and medial retractors still in place, the femoral implant is placed onto the distal femur (A) with the femoral impactor (B) to achieve correct positioning of the femoral component. This positioning can be verified again with the resection plane probe and visualized on the screen.

analgesics. Physical therapy is started as early as 5 to 6 hours post-operatively under the supervision of a physiotherapist (ie, continuous passive motion 3 times a day, early ambulation, walking exercises, active bending and extending exercises, active knee stretching exercises, walking up and down stairs, ergometer-bicycle riding, coordination exercises, rising from a seated position,

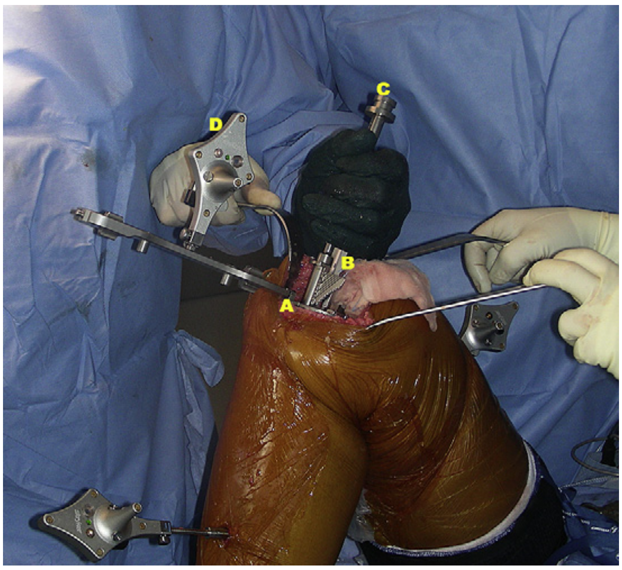

Fig. 13. Tibial rotation. The baseplate (A) is secured onto the tibial surface in the desired rotation. Then the preparation of the tibial keel is undertaken using the tibial punch tower (B) and tibial punches (C) under visual control on the screen with the universal tracker (D).

strengthening exercises, and other regimens). Patients are allowed to full weight bearing as tolerated. Patients are discharged from the hospital once they are able to flex the knee joint to 120°, perform an unassisted straight-leg raise, walk independently with or without crutches, rise from a chair to a standing position and sit from a standing position without support, and ascend and descend a full flight of stairs. All patients receive low molecular weight heparin for deep venous thrombosis prophylaxis for 6 weeks. Outpatient physical therapy is started after discharge. Patients are evaluated clinically and radiographically in the office at 6 weeks, 3 months, and 6 months.

CLINICAL EXPERIENCE WITH MINIMALLY INVASIVE COMPUTER-ASSISTED TOTAL KNEE ARTHROPLASTY

The author and his colleagues performed a comparative study in which 20 patients who had undergone conventional CN-TKA were compared with a directly matched group who had undergone MIS CN-TKA.[57]

Clinical Results

The two groups were matched according to gender, age, diagnosis, pre-operative deformity, etiology, range of motion, pre-operative Hospital for Special Surgery (HSS) knee score, Knee Society knee and function scores, major comorbidities, and duration of follow-up.[58,59] There were 11 women and 9 men in the conventional CN-TKA group and 12 women and 8 men in the MIS CN-TKA group. The mean pre-operative age was 67 years (range 37–87 years) for the conventional CN-TKA group and 68 years (range 48–76 years) for the MIS CN-TKA group. The mean pre-operative flexion was 120° (range 110°–130°) for the conventional CN-TKA group and 118° (range 110°–127°) for the MIS CN-TKA group. The mean pre-operative mechanical axis was 4.5° valgus (range 18° varus/16° valgus) for the conventional CN-TKA group and 4.7°valgus (range 16° varus/ 13° valgus) for the MIS CN-TKA group. No significant differences between the two groups were seen for age, gender, pre-operative mechanical axis, flexion, HSS knee score, functional knee score, and American Knee Society score. Inclusion and exclusion criteria and further demographic data are available on request from the author.[57] In the conventional CN-TKA group a standard medial parapatellar approach was used, whereas in the MIS CN-TKA group a midvastus approach was used.

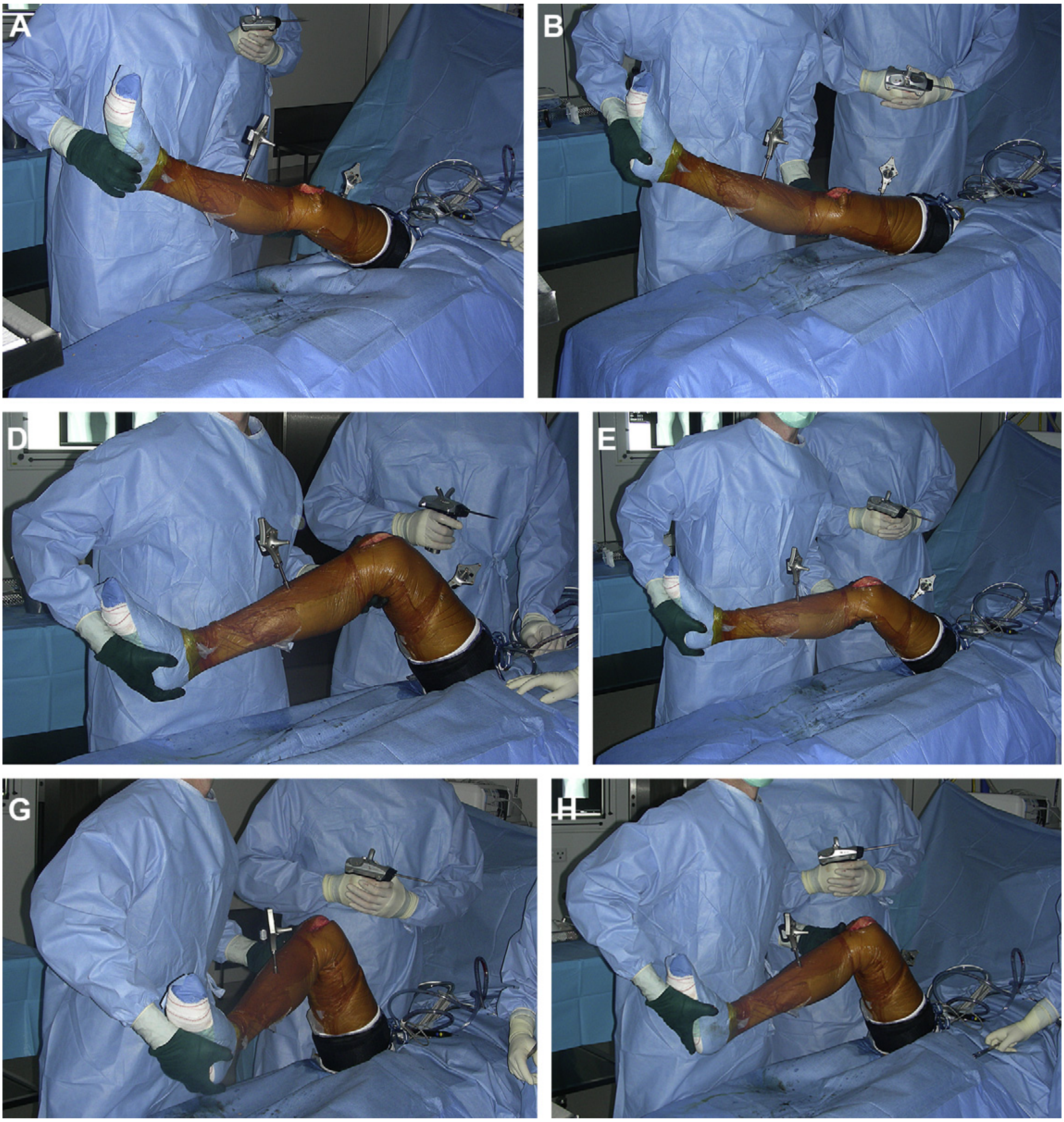

Fig. 14. The assessment of the joint kinematics with the computer-navigation: The kinematics of the knee can be assessed in a dynamic way moving the knee joint from maximal extension to deep flexion under no stress (Figures A, D, G), under manual varus stress (Figures B, E, H) and under manual valgus stress (Figures C, F, I) by maintaining the limb in the same rotation through the heel of the foot. The first line (Figures A-B-C) represents the knee joint position in 0° flexion/extension, the second line (Figures D-E-F) the knee joint position in 45° flexion/extension and the third line (Figures G-H-I) the knee joint position in 90° flexion/extension.

No difficulties in exposure and visualization were encountered in obese patients, patients with large knees, muscular male patients, or patients with more severe deformities. The author and his colleagues also have had no complications with the navigation system or reference pins. No complications (ie, fracture, revision, manipulation, deep infection, hematoma, clinically evident deep vein thrombosis, or major cardiopulmonary complication) occurred intraoperatively or postoperatively. There was no compromised implant fixation evident on follow-up. All patients recovered well after the operation.

The mean post-operative range of motion after the first 3 months was significantly higher in the MIS CN-TKA group (125°) than in the conventional CN-TKA group (118°) (*P* = .037). Six months after the operation, however, there was no statistically

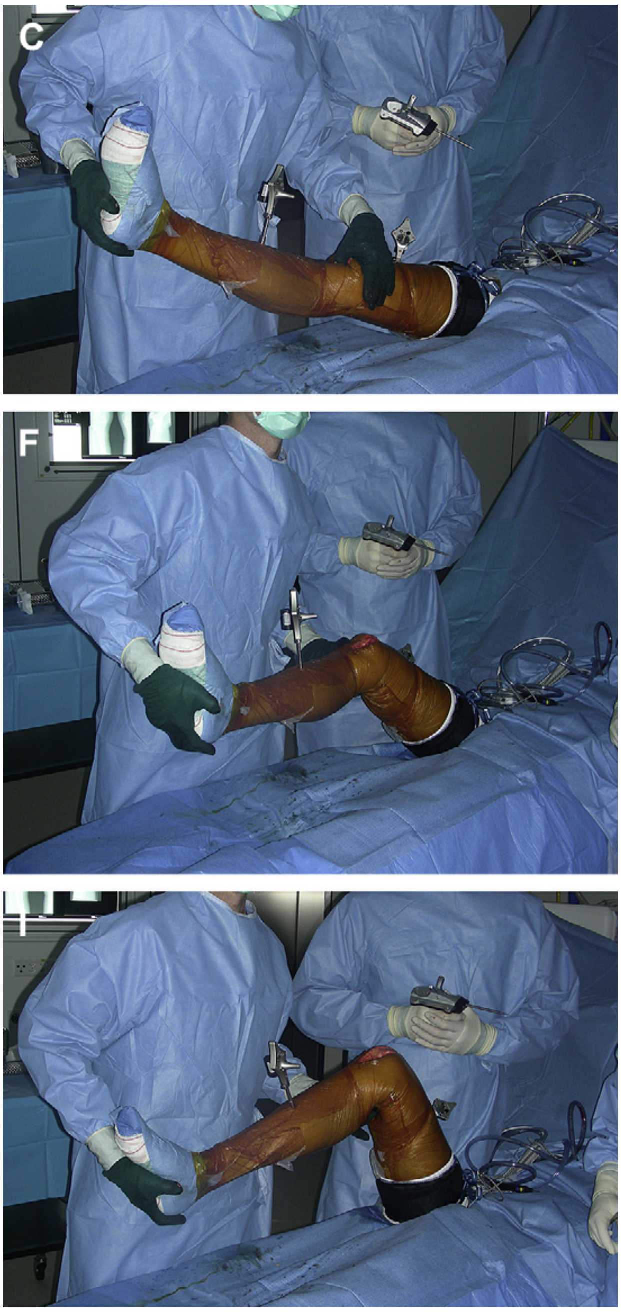

Fig. 14. (*continued*)

relevant difference between the two groups in range of motion (125° versus 122°). The HSS knee score improved in both groups to almost identical values during the first 6 months after the operation. The Knee Society clinical rating score (ie, the knee and function scores) also showed no significant difference between the groups during the first 6 months after surgery. The author and his colleagues found no statistically significant differences between the MIS CN-TKA group and the conventional CN-TKA group in operating time and blood loss.

Radiographic Results

All patients received full-length standing anteroposterior radiographs pre-operatively and 6 weeks postoperatively. Full-length full-weight-bearing standing anteroposterior radiographs were performed with the automated Philips Multidiagnost 3 (Philips Medical Systems, DMC GmbH, Hamburg, Deutschland). Pre- and post-operative mechanical axes (ie, the coronal mechanical axis of the limb, the hip-knee angle) were determined from radiographs. A mechanical axis of more than 3° varus/valgus was determined as an outlier, as defined previously.[17,18] Conventional radiographic assessment involved short-leg-length weight-bearing anteroposterior radiographs, as well as nonrotated short-leg-length lateral radiographs at 30° of knee flexion and patella axial radiographs pre-operatively and 6 months after the operation. The alignment of the prosthetic

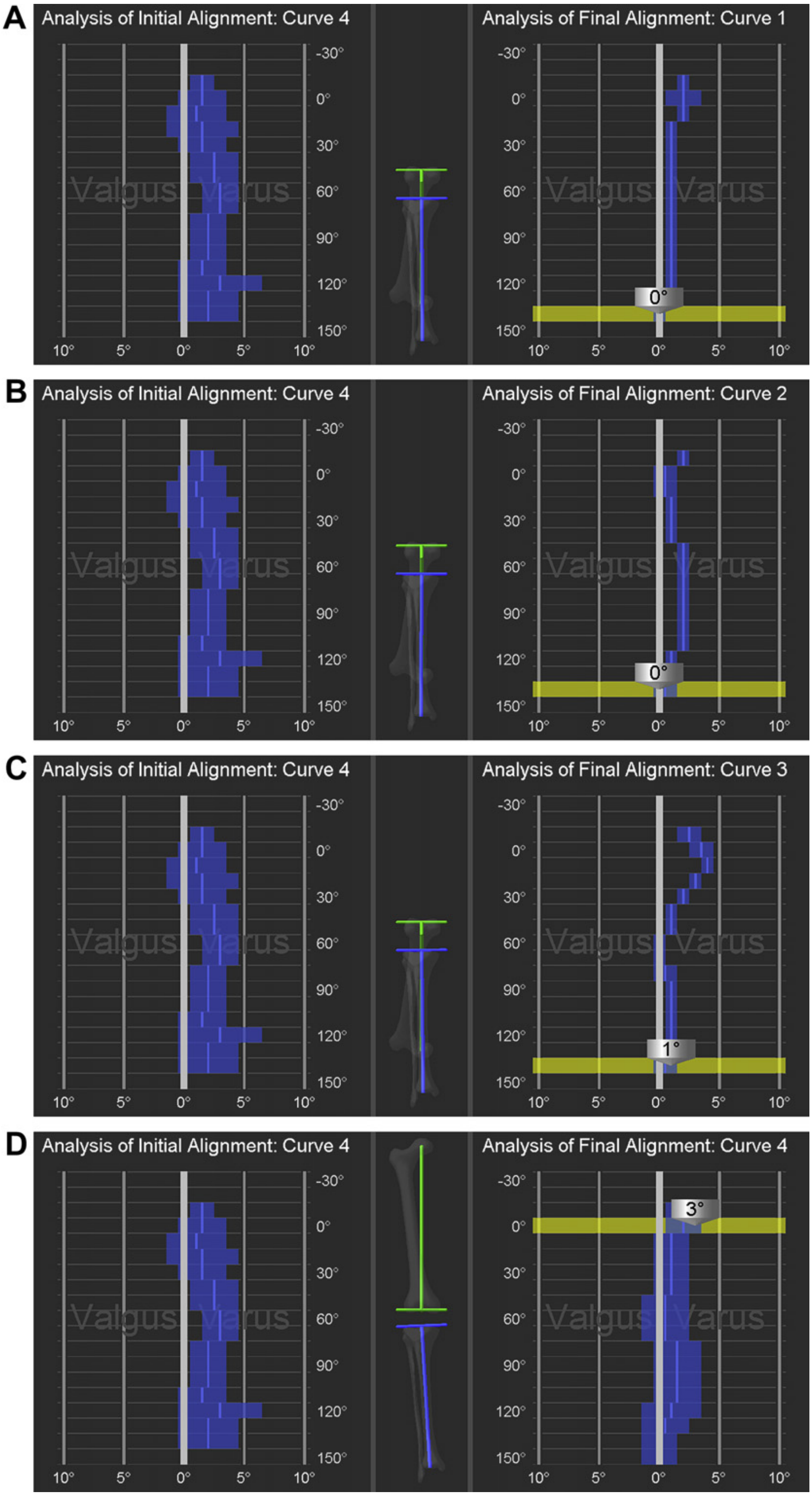

Fig. 15. The range of motion, the alignment of the limb, and the stability of the medial and lateral joint space can be verified, recorded and compared to the initial kinematics data on the screen under no stress (*A*), under manual varus stress (*B*), and under manual valgus stress (*C*). It still is possible at this stage to assess the complete joint stability and soft tissue balance under maximal varus and valgus stress by using different sizes of polyethylene trials and the final kinematic analysis screen (*D*) prior to inserting the definitive insert size.

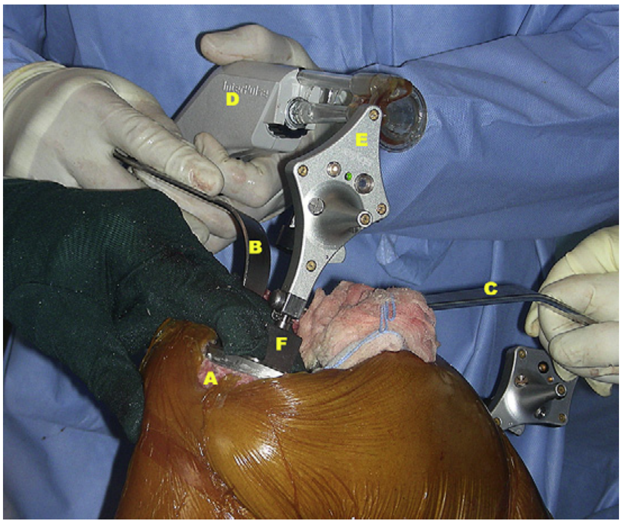

Fig. 16. Definitive insertion of the tibial baseplate component (A). With the knee flexed, two retractors are used to protect the soft tissues on the medial and lateral aspect (B). A giraffe retractor (C) is placed posteriorly to deliver the tibia lightly forward. After the tibial surface is cleaned with the pulsating lavage device (D), the tibial baseplate (A) is inserted into the keel cut and cemented down into the desired position, which is checked with the universal tracker (E) and the resection plane probe (F).

Fig. 18. The patellar component (A) is inserted with cement (B), which can be removed with a knife under good visualization.

components was evaluated on the short-leg-length standard radiographs. Radiographic parameters including the coronal femoral component angle, the sagittal femoral component angle, the coronal tibial component angle, and the sagittal tibial component angle (ie, tibial slope angle) were evaluated to assess the correct positioning of the femoral and tibial components.[60] The coronal alignment of the femoral component was measured in relation to the anatomic femoral axis (ideal value 96°) and of the tibial component in relation to the anatomic tibial axis (ideal value 90°) (**Fig. 21**). To determine the sagittal angle of the femoral and tibial components respectively, a perpendicular line drawn from the midline of the femoral tibial components was compared with the midline of the distal segment of the femur and of the proximal segment of the tibia using the Knee Society score reference lines.[61] Although there is little consensus about the ideal reference for measuring the slope of the tibia on the lateral radiograph, the author and his colleagues used the technique described by Catani and colleagues[16] and Yoo and colleagues[62] measuring the slope of the tibial component on conventional short-length sagittal-view radiographs with

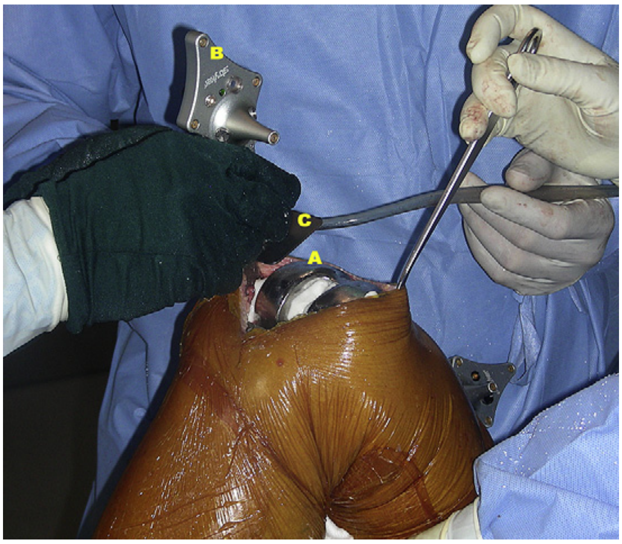

Fig. 17. Definitive insertion of the femoral component. After the femoral surface is cleaned with a pulsating lavage device, the femoral component (A) is inserted and cemented in the desired position, which is checked with the universal tracker (B) and the resection plane probe (C). When the component is in the desired position, any excess cement can be removed.

Fig. 19. The wound (A) is closed, and the pins, including the trackers, are removed. (B) marks the tibial wound.

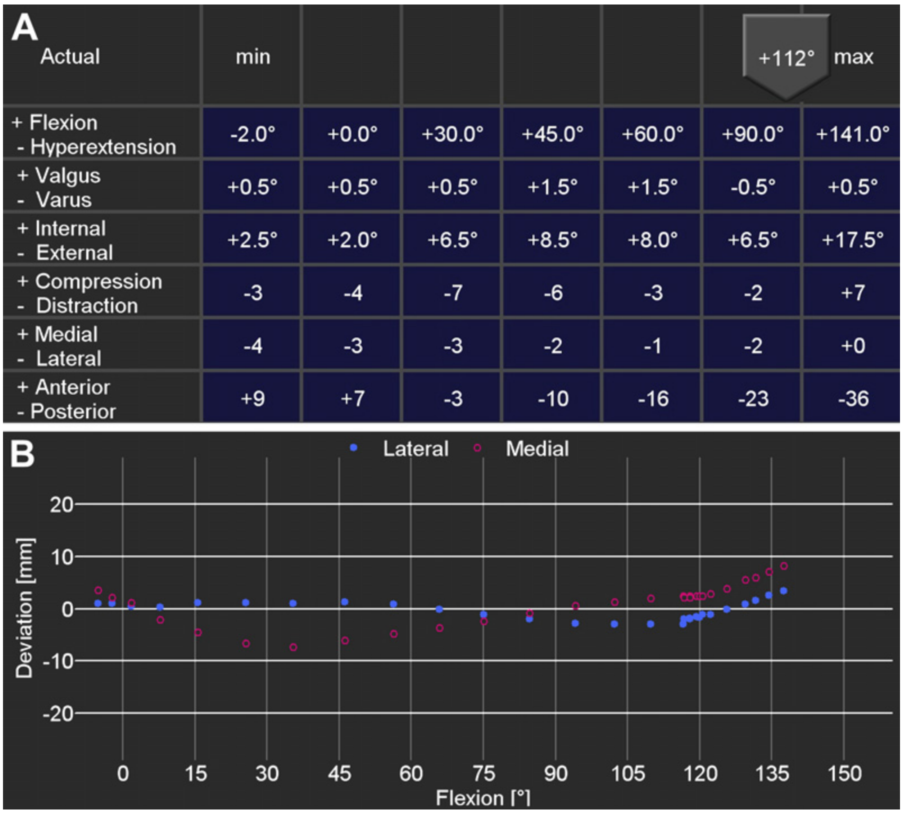

Fig. 20. The final kinematics and outcome are documented on the screen as a value (*A*) and as a curve (*B*).

reference to the proximal anatomic axis. The pre- and post-operative sagittal tibial component angle (ie, tibial slope angle) was compared on conventional short-length lateral radiographs in 30° of knee flexion.

The radiographic coronal mechanical axis of the limb (ie, the hip-knee angle) improved to normal values in both groups (0.5° in the conventional CN-TKA group and 0.7° in the MIS CN-TKA group). There were no alignment outliers in the mechanical axis in either group postoperatively (**Fig. 21**). With regard to the accuracy of the coronal alignment of the femoral component (ideal value 96° in relation to the anatomic femoral axis), the author and his colleagues found a correct implantation of the femoral component in all cases, with no statistically significant differences between the conventional CN-TKA group (mean value 96.2°) and MIS CN-TKA group (mean value 95.2°) (see **Fig. 21**). They found the same accuracy for the implantation of the tibial component in the coronal alignment (ideal value 90° in relation to the anatomic and mechanical tibial axes), with no statistically significant differences between the conventional CN-TKA group (mean value 91.3°) and the MIS CN-TKA group (mean value 91.4°) (**Fig. 21**).

The post-operative radiographic analysis of the sagittal alignment of the femoral component in relation to the anatomic femoral axis revealed slightly greater flexion of the femoral components in both groups in comparison with pre-operative planning (mean value 6.9° in the conventional CN-TKA group versus 7.8° in the MIS CN-TKA group) (**Fig. 22**). The intraoperative alignment of the sagittal femoral cut showed an accurate value close to the 1° of flexion planned pre-operatively in both the conventional CN-TKA group (mean value 0.58°, SD 0.44°, range 0.0°–1.5°) and the MIS CN-TKA group (mean value 1.03°, SD 0.40°, range 0.5°–2.0°). This difference might be explained by the use of different methods to determine the sagittal femoral components angle intraoperatively and postoperatively. The intraoperative measurements of femoral bone resection in the sagittal plane were assessed with the navigation system, which measures this angle in relation to the mechanical axis, whereas the post-operative measurements were performed with a short-leg lateral radiograph at 30° of knee flexion, which defines this angle in relation to the anatomic axis of the femur. The tibial slope was reconstructed to match the pre-operative value both in the conventional CN-TKA group (mean value 1.6°) and in the MIS CN-TKA group (mean value 1.4°) (**Fig. 22**).

All patients also received standardized CT scans of both knees 6 weeks postoperatively to evaluate rotational alignment of the components.[63]

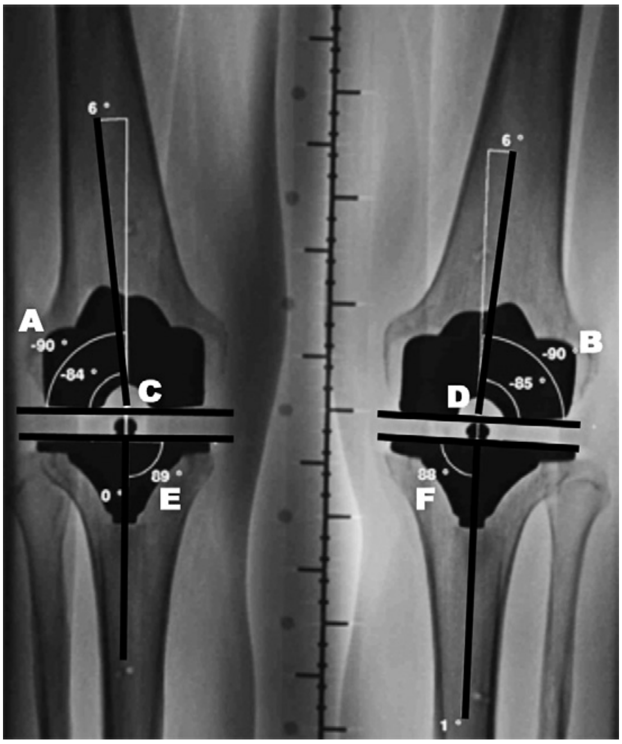

Fig. 21. The postoperative mechanical axes (A and B angles) (ie, the coronal mechanical axis of the limb) (*white line*) after a bilateral MIS CN TKA with straight axes on both sides. The coronal alignment of the femoral component is measured in relation to the anatomic femoral axis (*black line in the femur canal*; ideal value 96°) and of the tibial component in relation to the anatomic tibial axis (*black line in the tibial canal*; ideal value 90°). The coronal alignments of the femoral (angles C and D) and tibial components (angles E and F) are correct at both sides as well.

Fig. 22. Analyses of the sagittal alignment on postoperative short-leg-length lateral radiograph at 30° of knee flexion: the sagittal femoral component angle (angle A) and the sagittal tibial component angle (angle B) (ie, the tibial slope). The slope of the tibial component (B angle) is measured with reference to the proximal anatomic axis (C).

Multislice CT scans of the knees in 5-mm slice thickness and 2-mm slice distance were obtained using a GE Lightspeed multislice scanner (GE Medical Systems, (Schweiz) AG, Glattbrugg, Switzerland). The analysis of the post-operative CT scans revealed a statistically significant reconstruction of the desired rotational alignment of the femoral component parallel to the transepicondylar axis in both the conventional CN-TKA group (mean value 0.7°) and the MIS CN-TKA group (mean value 1.3°) (P = .018). The author and his colleagues were not able to document any outliers in terms of rotational alignment of the femoral prosthesis.

DISCUSSION

Malposition of TKA affects implant fixation and leads to an increased risk of loosening and instability and to decreased survival of the prosthesis. Computer-assisted navigation systems have been designed to increase the precision of TKA implantation. Computer-assisted TKA implantation allows the surgeon to reproduce the mechanical axes measured on full-length standing radiographs of the lower limb and reduces the number of outliers in the alignment of the limb compared with traditional mechanical instrumented TKA.[9,23–27,29–31] Furthermore, although analysis of alignment and component orientation after computer-navigated and conventional implantation shows contradictory results, two recent meta-analyses of alignment outcome for computer-assisted versus conventional TKA indicate significant improvement in component orientation and mechanical axis when computer-assisted navigation is used.[64,65]

Our comparative study demonstrated that it is possible, by using a computer-assisted navigation system, to achieve straight mechanical axes using either a conventional or a minimally invasive approach. No outliers were found in either group. Furthermore, the intraoperative alignment of the femoral and tibial bone resection was accurate in all three planes in both the conventional CN-TKA and the MIS CN-TKA groups. Similar intraoperative results have been published, and our results showed the same accuracy using the navigation system the intraoperative bone resections as reported in the previous studies.[9,24–26,28]

The limits of these meta-analyses warrant further discussion, however, because the mechanical axis may be a parameter too simple to use as an indicator of limb alignment and better long-term outcomes. Accurate angles of the individual components in the coronal and sagittal plane, correct rotation, and proper ligament and soft tissue balancing contribute to the success of knee replacement surgery. Various studies have compared component orientation performed with computer-assisted systems versus traditional implantation. All these studies, however, have investigated TKA implanted using conventional approaches. Most authors showed that the coronal alignment (ie, the varus/valgus alignment) of the femoral component was improved with the use of computer navigation.[9,19,24–26,60,66–69] Only few studies did not report an improvement in component alignment when computer navigation was used.[70,71] Even though the senior authors in these studies have more experience with conventional TKA than with navigated TKA, there were fewer outliers in the navigation group. We were also able to demonstrate that, using a commercially available computer-assisted navigation system, it is possible to implant the femoral and tibial components in the desired coronal planes with either the conventional approach and with a minimally invasive approach. The post-operative radiographic analyses of the coronal alignment of the femoral and tibial components showed reliable results in both groups, without any outliers in either group.

Sagittal alignment of the femoral component can be improved with the use of navigation in conventional approaches.[9,19,24,25,30,66,67,69] We were able to implant the femoral and tibial components in the desired sagittal plane in MIS CN-TKA as well as in conventional CN-TKA.

The influence of navigation on the alignment of the tibial component remains unclear. Several authors confirmed that the coronal alignment of the tibial component (ie, the varus/valgus alignment) is improved with the use of navigation.[9,24,69] Other authors, however, did not find an improvement in the coronal alignment of the tibial component.[19,30,62,63] We found the same accuracy for the implantation of the tibial component in the coronal plane the conventional approach and in the minimally invasive approach. Furthermore, we showed that the sagittal-tibial component angle (ie, the tibial slope angle) can be reconstructed accurately and reproducibly to match the original value of the tibial plateau in both computer-assisted approaches. Although some studies did not find that the alignment in the sagittal plane of the tibial component was improved with navigation, our results confirmed, as has been reported by other authors, that the surgeon can use computer-assisted navigation as a practical means to restore the tibial slope accurately during MIS CN TKA.[19,24,25,28,30,67,72–74]

Debate still exists about whether a navigation system improves the rotational alignment of the femoral component.[75] Several reference axes have been proposed to establish proper rotational alignment of the femoral components.[72] Of these axes, the transepicondylar axis approximates the flexion-extension axis of the knee. Furthermore, although there is no consensus about the best landmarks to gauge femoral rotation, alignment according to the surgical epicondylar axis seems to come closest to allowing physiologic biomechanics.[7,8,10,76] Debate continues about how accurately and easily the transepicondylar axis can be located intraoperatively. In a cadaver study, Siston and colleagues[72] found high variability in the rotational alignment of the femoral component. This variability may be explained by the surgeon's greater or lesser ability to identify intraoperatively the medial epicondyle with its bone ridge and sulcus and the attachment of the deep and superficial fibers of the medial ligament (see **Fig. 5**), by the learning curve for the surgeon associated with the use of navigation, and by the skills of the individual surgeon. Stöckl and colleagues[25] reported the same accuracy in finding the proper femoral rotational alignment with a conventional approach as with the Stryker navigation system. The algorithm used by the Stryker Knee Navigation Software to establish the proper femoral rotational alignment by averaging the angle subtended by the Whiteside line and the transepicondylar axis makes it possible for the surgeon to improve the accuracy of the femoral rotational alignment without unduly increasing the operative time. The analysis of our post-operative rotational alignment of the femoral component by CT scans revealed a statistically significant reconstruction of the desired rotational alignment of the prosthesis parallel to the transepicondylar axis in both the conventional and the minimally invasive computer-assisted navigated approaches. We found no outliers of the femoral rotational alignment in either group. These results are in agreement with other studies using standard approaches, computer-assisted navigation, and an improved CT protocol.[24,25,77] Accuracy in adjusting the rotational alignment of the femoral component is a prerequisite to avoid malfunctioning TKAs. Even small abnormalities of the rotational alignment of the components have a considerable influence on patellar tracking, on stability, and on the overall biomechanics of the joint. To the author's knowledge, this study is the first comparative study using a CT technique and a minimally invasive approach that shows it is possible to adjust the rotational alignment of the femoral component accurately and reproducibly by using a computer-assisted navigation in both conventional and minimally invasive approaches.

Although it has been reported that the rotational mismatch between the femoral and tibial components is decreased with navigation, controversy still exists as to whether navigation systems improve the rotational alignment of the tibial component in the axial plane.[24,78] We used the technique describe by Dalury[55] and Eckhoff and colleagues[56] in which the orientation of the tibial tray was determined by allowing it to float into position with respect to the femoral component while the knee was placed through a full arc of motion and were able to document an accurate alignment of the tibial component in the CT scan. We believe, however, that a navigation system that relies only on digitization of landmarks to establish the rotational alignment of the tibial component is not sufficiently reliable. Therefore further research is necessary.

Component malpositioning is not the only cause of long-term TKA failure. Instability, often representing a failure to correct the soft tissue and to balance the flexion and extension gaps at the time of the index arthroplasty, can lead to implant failure. In some studies, 30% to 35% of revision TKAs were caused by an uncorrected joint stability.[20–22] Stability of the knee involves ligaments that behave differently on the medial and lateral aspects. Medial–lateral instability is the most common type of instability and may result from incompetent collateral ligaments, incomplete correction of a pre-operative deformity, incorrect bone cuts, or incorrect restoration of the original joint line. A stable knee joint maintains an appropriate minimum contact force between the articulating surfaces throughout the functional range of motion. Thus, a TKA is stable when, moving through its range of motion, it can undertake the required functional loads without pain, maintaining contact on nonperipheral located regions, and produce a joint contact force of normal intensity on the polyethylene insert. Any factors causing an abnormal joint contact force and/or an abnormal eccentric position of joint contact force might lead to polyethylene and component loosening. The TKA stability and function are related directly to the interplay among the implant component alignment, articular surface geometry (flat or congruent polyethylene insert), cruciate-retaining or cruciate-substituting prosthesis design, soft tissue balancing, and muscle action. Of these factors, implant component alignment, joint-line restoration, and soft tissue balancing can be and should be assessed and restored by the surgeon during the surgery. The joint-line height both at the femur and tibia usually is calculated using measurements on pre- and post-operative radiographs and standard anatomic indices. The Knee Navigation System allows the surgeon to measure and restore the femoral joint height and the tibial joint line (**Fig. 23** A–C).[79]

To avoid incorrect location of the joint line, the surgeon can measure the tibial and femoral joint-line heights intraoperatively with the Knee Navigation System. The surgeon also can measure the variance of this line: the tibial joint-line variation is the difference between pre-operative and post-operative tibial heights; therefore a negative value indicates tibial elevation. A similar calculation can be performed on the femoral side.[79] These measurements, however, are affected by soft tissue release, which is difficult to quantify intraoperatively. Furthermore, an established concept has been the preparation of a rectangular joint gap in TKA. With a posterior-stabilized TKA, flexion and extension gaps can differ. A rectangular joint gap has been regarded as an important goal for achieving good joint function. The lateral tibiofemoral joint is physiologically lax, however, and as consequence the flexion gap may not be rectangular. In a cadaveric study on normal, nonarthritic knee joints, Van Damme and colleagues[80] reported greater lateral than medial laxity in full extension and increased lateral laxity from 0° to 90° flexion. Because of technical difficulties, few data are available on the physiologic laxity of the joint. Such analysis can be performed only if the flexed knee is imaged three-dimensionally both in neutral position and under a varus/valgus stress. Developments in MRI now allow the living knee to be imaged in a variety of positions and flexion angles. Tokuhara and colleagues[81] analyzed quantitatively the stability of the medial and lateral tibiofemoral joint for normal knees in open MRI. Their results indicate that the flexion gap in a normal knee is not rectangular and that the lateral joint gap is significantly lax. Recent biomechanical studies have shown further that flexion of the knee is associated with a significant medial-pivot internal rotation of the tibia.[82–85] Thus, in rotation the medial condyle is immobile, and the lateral condyle is mobile on the tibial surface. Since 1977, several studies using optical encoders, pressure-sensitive film, fluoroscopy, or a knee analysis system have investigated the relationship between soft tissue release and the resulting changes in the tibiofemoral gaps in TKA.[86–89] Most of these methods are difficult to use in routine TKA practice because of ergonomy, cost,

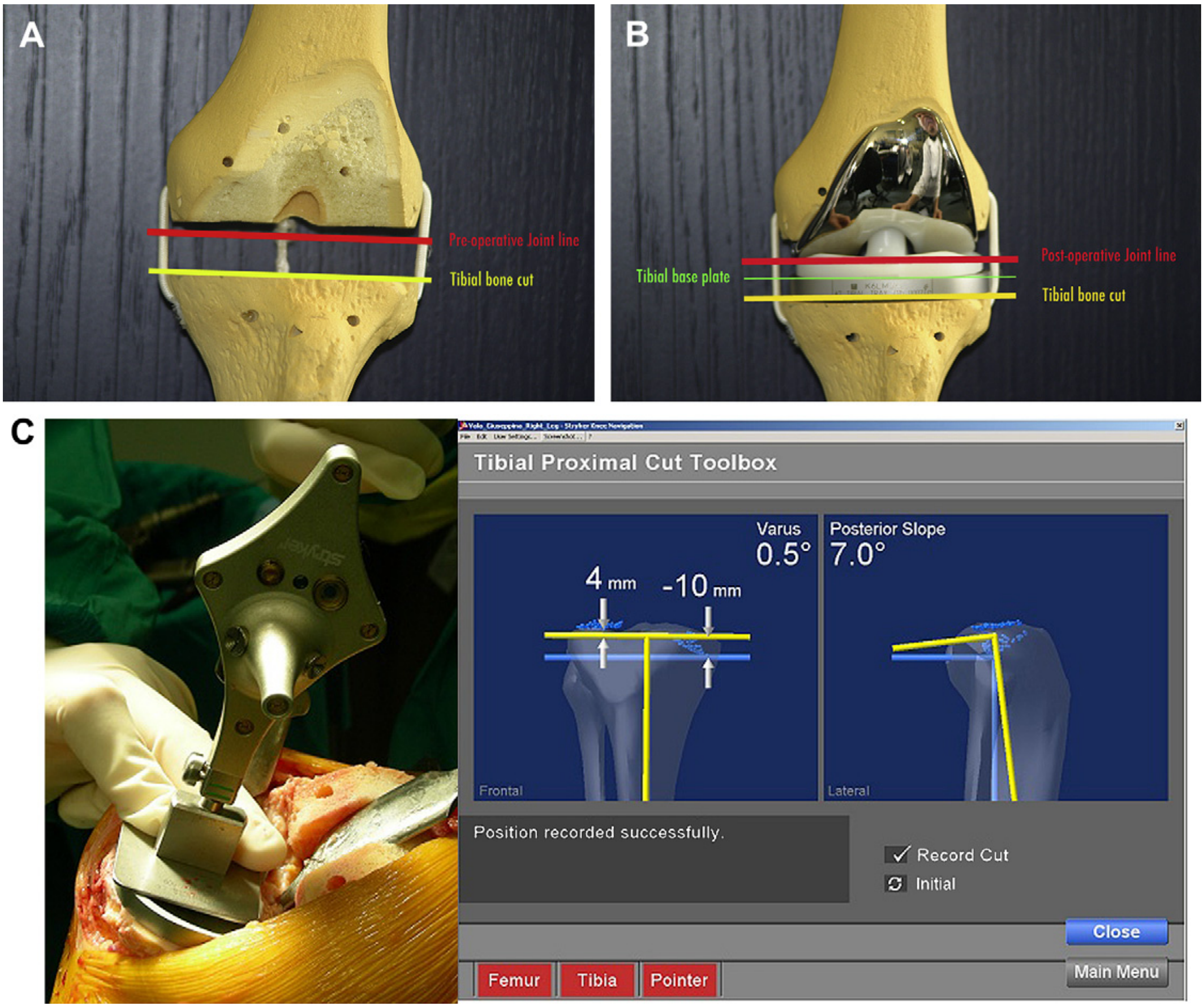

Fig. 23. Models showing measurement of the tibial joint line. (*A*) The height of the pre-operative tibial joint line (*red line*) is measured by digitalizing the deepest points on the two tibial condyles with the Knee Navigation System. The yellow line indicates the tibial bone cut. (*B*) The height of the postoperative tibial joint-line height (*red line*) is calculated by measuring the height of the tibial base plate with the resection plane probe and the thickness of the polyethylene. (*C*) Intraoperatively, the surgeon can measure the tibial joint line with the universal tracker with the resection plane probe (*left*). The corresponding medial and lateral heights are stored on the persona computer screen (*right*).

or safety. Computer-assisted surgical technology enables surgeons to measure and assess knee behavior during surgery, allowing real-time monitoring of the knee's behavior from extension to flexion and soft tissue balance. In a previous study, we measured the mechanical axis and the varus/valgus stability of the joint at different time points using the computer-assisted knee navigation, and we documented a similar increased lateral joint laxity before and after implantation of the components at 45° and 90° of knee flexion.[90] Therefore, knee navigation enables the surgeon to monitor and to quantify objectively what the surgeon used to feel and estimate in the past: the kinematics and stability of the TKA through the full range of motion pre-, intra- and postoperatively. Leaving the knee too lax after TKA theoretically may lead to tibiofemoral instability, and excessive tightness may cause stiffness. The assessment of laxity is a new step in using the computer intraoperatively for balancing soft tissue safely. Unlike TKA alignment, however, no data are available to define a well-balanced knee intra- and/or postoperatively. As ideal laxity for TKA, we suggested a varus/valgus laxity of an approximately total joint-line opening between 1.5° to 2° to be achieved over the whole range of motion.[90] These findings serve as a benchmark for future measurements of soft tissue laxity, and these proposed values should be validated by additional work. The computer will help correlate the collected data and clinical outcomes more objectively than in the past and enable the setting of more accurate limits for soft tissue management.

Recently, various authors have reported superior clinical results and decreased cost using MIS techniques for TKA.[35,37,40,41] The conventional surgical approaches and instrumented techniques seem to cause much more soft tissue damage, leading to a very long recovery period. Although the length of the skin incision is shorter in the MIS approach, MIS knee surgery should not be defined by the size of the skin incision but rather by the method of soft tissue handling once the skin is incised. We believe that minimal trauma of the soft tissue and bone results in better post-operative function and accelerated rehabilitation. In our study, we were able to demonstrate that MIS CN-TKA can achieve these objectives. Although we could not find any statistical differences 6 months after the index operation, patients in the MIS CN-TKA group improved their range of motion faster than those in the conventional CN-TAK group. This difference was only significant 3 months postoperatively, however. These results are consistent with the experience of other studies on minimally invasive surgery.[31,41,91–93] Furthermore, there was no difference between the two groups in operation time or blood loss as measured by post-operative change in hemoglobin. With the minimally invasive approach, patients were mobilized more aggressively, reaching full weight bearing and leaving the hospital earlier. We also observed no significant differences between the conventional CN-TKA and MIS CN-TKA groups in HSS and Knee Society scores after 6 months. These clinical scores, however, are not ideal for the evaluation of patient satisfaction soon after a computer-navigated TKA with a conventional or MIS approach.[94] It would have been more appropriate to use patients' self-reported measures of outcome, such as the Western Ontario and McMaster Universities Index of Osteoarthritis and the Short Form-36 scoring systems.[43] In addition, a prospective, randomized, controlled study demonstrated a positive correlation between accurate mechanical alignment after TKA and functional and quality-of-life outcomes.[43] At all post-operative follow-up intervals from 6 weeks to 12 months, the total Knee Society score was significantly better in patients who had a mechanical axis within 3° of neutral than in those who had a mechanical axis greater than 3°. Moreover, the Short Form-12 (SF-12) physical scores at all intervals from 3 months on were significantly better for patients who had a mechanical axis within 3° of neutral, and at 12 months these patients demonstrated better SF-12 mental scores as well. Additionally, TKA with good alignment can lead to better function with quicker rehabilitation and earlier hospital discharge.[44] Therefore, the use of computer-assisted navigation leads not only to reproducible accuracy of implant positioning in all three planes but also to better functional outcomes with quicker rehabilitation and earlier hospital discharge because of the advantages of minimally invasive techniques.

POTENTIAL PITFALLS OF MINIMALLY INVASIVE COMPUTER-ASSISTED TOTAL KNEE ARTHROPLASTY

The primary risk of computer-assisted navigation is for the surgeon to lose perspective regarding the value of the system. The system is very sophisticated and, if used correctly, will improve accuracy. The system enhances the surgeon's perspective but should never replace it.

MIS CN-TKA is a more challenging procedure than a standard TKA. Complications may be reduced, but surgical risks to avoid include

- Excessive traction to the skin with skin breakdown
- Malfunctioning of the navigation system (ie, dirty reflectors, camera or rounding errors) or of the reference pin (ie, intraoperatively loosening of the pin and consequent inaccuracies in reference reading)
- Stretching against the quadriceps mechanism, which can cause intrinsic damage to or shredding of the muscle
- Inappropriate patella bone resection with the risk of a post-operative fracture or patella overstuffing
- Inaccurate identification of the anatomic landmarks at surgery
- Avulsion of the patellae tendon or injury to the patella by excessive traction on the patella
- Inappropriate bone cut caused by decreased visualization
- Inappropriate osteophytes/cement removal caused by decreased visualization
- Femoral and tibia mal rotation, malalignment, and malpositioning
- Difficult tibial keel preparation with risk of damaging the lateral femoral condyle
- Inadequate cement pressurization and implantation

Although excellent results may be achieved with computer-assisted navigation, certain factors still are cause for concern intraoperatively. If the patient has severe osteopenia, the pins placed in the bones to hold the trackers may become loose, making all further measurements inaccurate. Therefore, the surgeon must be very careful when handling pins and trackers. Likewise, because only the cutting guides are navigated, the surgeons may make less-than-optimal bone resections by bending the saw blade, especially when attempting to cut through sclerotic areas of bone. Also, differences in cement thickness may lead to malalignment, even though the bone resection was accurate. These latter two problems, which can occur with conventional instrumentation as well, can be obviated with the computed-assisted navigation only by using the verification plate of the Knee Navigation System, which allows the surgeon to check every cutting procedure during the operation and to verify the correct level of the joint line.

ADVANTAGES OF COMPUTER-ASSISTED MINIMALLY INVASIVE TOTAL KNEE ARTHROPLASTY

The use of computer-assisted navigation leads to reproducible accuracy of implant positioning in all three planes in both conventional and minimally invasive approaches. In contrast to even the most elaborate mechanical instrumentation system, which relies on visual inspection to confirm the accuracy of the alignment and stability of the TKA, computer-assisted navigation allows the surgeon to verify every operative cut by using the resection plane probe, which allows three-dimensional control of the cut planes on the screen, of the position of trial components, and finally of the position of the implants. In addition, computer-assisted technology assists the surgeon in reliably measuring the kinematics of TKA alignment and the stability of the TKA on a screen. Furthermore, surgeons have the opportunity to improve their surgical performance with a direct intraoperative documentation of the alignment and orientation of instruments, trial components, and implants. These advantages improve the accuracy of every single cut. Furthermore, the computer-assisted navigation allows the surgeon to verify the final alignment of the implants after component implantation and before the cement hardens, an ability the author believes is important to avoid considerable error in alignment. The conventional technique is limited by the dependence on extramedullary alignment guides or intramedullary rods. Correct positioning of the components, however, may only be a co-factor, together with instability and soft tissue trauma with the minimally invasive approach, leading to suboptimal implant loading with early loosening and increased wear. The use of computer-assisted navigation alone will not empower the surgeon to implant a TKA accurately and reproducibly, especially if the minimally invasive technique is used. Technical expertise in the conventional TKA and the surgeon's skill and familiarity with the instruments also are necessary to obtain good results.

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