(iv) Computer-assisted knee replacement techniques

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Summary
Implant alignment errors are associated with inferior results after total knee arthroplasty. Computer assistance supplements mechanical instrumentation by the addition of measurements which are used to locate landmarks, direct surgical tools and thereby better align prosthetic components. Modern navigation systems are based on infrared-light tracking or, more recently, on electromagnetic guidance. After initial scepticism a variety of systems have found acceptance and a remarkable number of clinical and laboratory studies have been published. There appears to be a consensus that computer assistance brings about a significant reduction in the number of outliers and improved varus/valgus, rotation and slope alignment of components. Most studies conclude with the prediction that individual and cumulative improvement in component alignment will ultimately lead to better long-term results. The controversies surrounding routine use of computer assistance in knee arthroplasty are discussed. Data analysis founded on navigated dynamic intra-operative investigation will possibly be the key to future implant design and alignment.

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Introduction

Knee replacement surgery has gained the reputation of generally being successful. Patients assume that well-trained orthopaedic surgeons consistently operate to produce satisfactory results. The term “satisfactory” embraces a range of good and acceptable outcomes. Nevertheless, outcome studies have made it clear that even experienced surgeons, using conventional knee replacement techniques, are occasionally faced with major post-operative limb mal-alignment and errors of implant positioning. Such cases are confined to difficult clinical situations such as obese patients, dysplasia, trauma or metabolic disorders. Orthopaedic surgeons are in agreement that the outcome of total knee replacement surgery is sensitive to variations in surgical technique. Several studies have suggested that coronal leg alignment errors of more than 3° are associated with more rapid failure and inferior functional results after total knee arthroplasty. Major clinical problems can be related to poor component positioning, including sagittal plane and rotational mal-alignment. Exact axial alignment promotes longevity of the implant, mal-positioning can lead to loosening.

Mechanical alignment systems are being improved continuously. However, it has been estimated that errors in tibial and femoral alignment of over 3° occur in at least 10% of total knee arthroplasties, even when carried out by skilled surgeons using up-to-date mechanical alignment systems.
tools. Conventional systems have elementary drawbacks that limit their ultimate accuracy. Precision of pre-operative X-ray templating is limited by the errors inherent in measuring from radiographs. Intra-operative determination of crucial landmarks, such as the centre of the femoral head and the centre of the ankle, is hard to achieve. Most importantly, traditional alignment and sizing devices assume a standard bone geometry that may not apply to a specific patient. All available mechanical instrumentation systems rely on visual inspection to confirm the accuracy of implant placement and stability at the conclusion of the total knee replacement procedure.

Computer-assisted systems have been designed to address the limitations associated with mechanical instrumentation for knee replacement surgery.\textsuperscript{14,15,16}

In principle, computer-assisted alignment for knee replacement can be classified as navigation or robotics. Robotic systems use equipment that takes over part of the surgical procedure. Navigation complements mechanical instrumentation by the addition of measurements used to locate landmarks, direct surgical tools and thereby align prosthetic components. Image-free navigation systems acquire and feed back information during surgery. Image-based navigation systems use pre-operative CTs or intra-operative fluoroscopic images. Modern navigation systems function using infrared-light tracking or, most recently, electromagnetic guidance (Fig. 1).

**Operative technique: optical systems**

Optical navigation systems vary with regard to the method of handling by the surgeon. Some use special pointers connected to a PC, others use foot pedals or sterile touch-screens. The presence of a computer specialist is usually not required. Navigation instruments and an infrared camera communicate, either via active light-emitting diodes (active optical system) or reflective spheres mounted on navigation arrays (passive optical system). Positioning of these trackers in bone is achieved either through an additional surgical incision or within the operative site. Fixation is achieved using mono- or bi-cortical anchorage. Once registration of anatomical landmarks has been performed, rigid fixation of navigation arrays to anatomical structures has to be safeguarded.

The centre of the femoral head, as the proximal landmark for the physiological axis of the femur is identified by analysis of the rotational pivoting movement of the femoral tracker. Single-point referencing identifies the epicondylar axis, Whiteside’s line, the distal femoral and proximal tibial centres and the centre of the ankle joint. Some systems also use ankle movement, with trackers fixed to the foot, in order to determine the centre of the talus. Surface registration is carried out to identify abnormalities of the femoral condyles or tibial plateaus in order to allow reconstruction of the joint line. During the registration process information about the soft tissue condition and ligament tension is gained, which in turn allows for controlled release of contracted structures.

Initial data collected are used to identify the pre-operative status of the knee. Dynamic investigations can be performed in order to document the initial range of movement and soft tissue alignment. These data can be recalled during the operation, allowing for a strictly individual approach. Clinicians using navigation rely on the ability of the computer systems to use arithmetical algorithms, which can compensate for surgeon’s error during registration of landmarks.\textsuperscript{17} One striking example is the mathematical matching procedure used to identify the individual femoral rotation by taking into account Whiteside’s line, the epicondylar axis and alignment of the posterior condyles. The amount of data analysed simultaneously for these calculations is probably beyond the
that 96% of the navigated knees were within \( \pm 3^\circ \) of optimal leg alignment, compared to 78% after conventional surgery. Post-operative assessment was performed on long leg coronal and lateral films.

Perlick et al.\(^{19} \) analysed 50 CT-based navigated and 50 conventional knee arthroplasties. They established a significant improvement in prosthesis alignment with computer assistance but also documented considerably higher extra costs for pre-operative CT scans, time-consuming planning and lack of a ligament balancing module within the CT-based software.

CT-free navigation was used in a multi-centre study published by Jenny et al.\(^{18} \), who observed the mechanical leg axis within \( \pm 3^\circ \) in 88% of navigated knees, while only 72% of patients reached a comparable leg axis when using the conventional technique.

Oberst et al.\(^{22} \) presented the results of a controlled, prospective and randomised trial comparing navigation with conventional surgery. CT analysis revealed that all 12 navigated knees were within the interval of \( \pm 3^\circ \) varus/valgus deviation, in comparison with only 8 of 13 non-navigated knees. Analysis of femoral component rotation showed no difference between the two groups.

Chauhan et al.\(^{23} \) performed a cadaver trial and a controlled randomised clinical trial to establish the benefits of computer navigation in total knee replacement. The authors found varus/valgus alignment of the tibial component, tibial posterior slope, tibial rotation, femoral rotation and standing leg alignment significantly improved when using an imageless optical navigation system compared to the results using a jig-based conventional system. The clinical study, involving 70 knees, is particularly interesting because a specific CT protocol, with outcome measurements from defined mechanical and anatomical axes, has been used to accurately define coronal, sagittal and axial alignment characteristics of the femoral and tibial components.

Beaver et al.\(^{24} \) assessed post-operative CT scans (75 patients) in a controlled study, which showed a statistically significant improvement in component alignment when using computer-assisted surgery for femoral varus/valgus, femoral rotation, tibial varus/valgus, tibial posterior slope and tibial rotation. Blood loss was reduced, though navigated surgery was more time consuming (mean increase of 13 min).

Haaker et al.\(^{25} \) compared 100 conventionally implanted with 100 navigated knees and measured significantly better tibial and femoral component positioning, with less outliers in the computer-assisted group. The authors did not report any navigation-specific complications. A mean additional 10 min of operating time was considered acceptable.

Sparmann et al.\(^{1} \) conducted a prospective randomised and externally evaluated study to investigate 120 hand-guided and 120 navigated total knee arthroplasties. They found a highly significant difference in favour of navigation with regard to the mechanical leg axis, the frontal and sagittal femoral component axis and the frontal tibial component axis.

Stulberg\(^{26} \) has shown that mechanical total knee replacement alignment systems have a tendency to leave the knee in slight flexion, to hyperextend the femoral component, to posteriorly tilt the tibial implant and to internally rotate the femoral implant. If implant longevity, pain relief, and function are related to the accuracy of component positioning, the Stulberg study emphasises that current
Mechanical instrumentation is associated with decreased accuracy at each step of the procedure. Matsumoto analysed 30 CT-free navigated and 30 matched conventional manual implantations, comparing post-operative long-leg radiographs. The results revealed a significant difference in favour of navigation. Matsumoto suggested that surgeons using navigation systems should be aware of possible over-sizing of the femoral component.

Vitor et al. compared 50 fluoroscopy-based computer navigated knee arthroplasties to 50 conventional procedures in a prospective randomised controlled trial. They found variability in the coronal plane was significantly reduced after computer-assisted surgery when compared with conventional techniques. The maximum deviation between the calculated kinematic centre of hip rotation and the fluoroscopically determined anatomic centre of the hip was 5 mm (mean: 1.6 mm).

Chin et al. studied standardised long leg coronal and sagittal X-rays in 90 patients with knee arthroplasty prospectively, who were randomised into three groups with extra-medullary or intra-medullary tibial guidance and computer-navigated surgery. Results in the coronal view revealed that 93.3% of patients in the computer-assisted group had ideal outcomes compared with 73.4% in the extra-medullary group and 60.0% with intra-medullary guidance. Equivalent results were found for the sagittal view.

Kim et al. prospectively compared 69 total knee arthroplasties using imageless computer-assisted navigation with 78 manually instrumented knees. Coronal alignment in full length standing radiographs revealed a larger variation in alignment in the manual group; 58% within 2 degrees of neutral, compared with 78% of the navigated group.

Anderson and colleagues evaluated the early outcomes of 116 navigated consecutive knee replacements and 51 conventional operations. The post-operative mechanical axis was within 3° of neutral mechanical alignment in 95% of the navigation cases versus 84% of the conventional cases. The number of outliers decreased with use of navigation.

Sikorski found computer assistance useful in revision situations in which significant bone deficits were encountered and bone grafting was needed. According to the author the remaining anatomical landmarks along with the old prosthesis, prior to removal, provide sufficient reference points to allow for controlled grafting or/cementation.

The use of imageless navigation, especially for ligament balancing in rheumatoid knee arthritis, appears to be useful because cutting errors can be detected and corrected intra-operatively.

Fehring et al. identified 18 knees believed not to be treatable using traditional instrumentation because of post-traumatic femoral deformity, retained femoral hardware, a history of osteomyelitis, or severe cardiopulmonary disease. Computer-assisted surgery was successfully used in 17 knees. The authors conclude that computer-assisted navigation was helpful in difficult situations where accurate alignment remains crucial, yet traditional instrumentation is not applicable.

The performance of integrated robotic systems for accurately machining bone surfaces has been evaluated. This includes cutting trials using plastic bones, followed by clinical trials in which the results of the anatomical registration and bone cutting have been noticed to be of high quality (Acrobot). Shi et al. presented a hand-eye robotic model for total knee replacement that combines with a movable hand-eye navigation system. Without using CT images and landmark pins in the patient’s bones, it is said to directly measure the mechanical axis with high precision.

Siebert et al. treated 70 patients suffering from idiopathic gonarthrosis with a robot-assisted technique using a commercial robotic surgical system (CASPAR) to assist in pre-operative planning and intra-operative execution. No major adverse events related to the use of this CT-guided robotic system have been observed. The mean difference between pre-operatively planned and post-operatively achieved tibiofemoral alignment was reported to be 0.8° (0–4.1°) in the robotic group vs. 2.6° (0–7°) in a manually operated control group of 50 patients. Because of better prosthetic alignment and improved bone-implant fit, implant loosening is anticipated to be diminished, which may be most evident in non-cemented prostheses. Disadvantages such as the need for placement of markers, increased operating times and higher overall costs were discussed.

**Discussion**

Accurate registration of anatomical landmarks is fundamental to the usefulness of computer-assisted orthopaedic alignment systems. The potential causes of registration errors using any given system must be understood by the surgeons who use these devices. The most important cause of registration inaccuracy is thought to be surgical technique. Registration errors might possibly be reproduced, and carried on through the navigated intervention up to final implantation of the implants. This is, in principle, true for mechanical as well as for navigated surgery. Navigation systems usually recognise large numbers of landmarks in order to determine one particular parameter. Thereby the initial registration error should be minimised.

Coronal alignment of the lower limb is particularly hard to define because of its wide variation among healthy individuals. Jenny et al. performed antero-posterior long-leg radiographs on 100 Caucasian patients without known knee abnormality. They found a wider than commonly estimated variation in the lower limb axes and concluded that for knee reconstruction the specific knee axes of the patient to be operated have to be taken into account. Individual re-alignment appears very valuable in unicompartmental knee replacements. It seems rather academic for total knee replacements, because individual (prearthritic) leg axes are unknown for patients with advanced bilateral tri-compartmental osteoarthritis.

Post-operative analysis of implant/leg alignment became a matter of debate with the introduction of navigation systems. It has now been accepted that plain radiographs provide a poor indication of overall alignment. Even if strictly standardised one-legged stance radiographs are taken, the measured alignment of the implant is not precise. Positioning errors of 2–3° have to be acknowledged with X-ray follow up. Therefore CT-based methods appear to provide the only reasonably accurate three-dimensional outcome study capable to assess possible cumulative error concerning mal-alignment of components. Yet again analyses are performed without definitive landmarks, limiting the value of conclusions drawn. Dynamic
intra-operative investigations performed using navigation systems (on-line tracing of component positioning during movement) will probably be the only way to find satisfactory answers concerning component position and to guide future implant design.

Jenny and Boeri\(^1\) concluded that to define the rotational alignment of a femoral component the trans-epicondylar axis may not be as reproducible as expected. This highlights the on-going debate about rotational alignment of components in knee replacement. The importance of the femoral rotation has been established to influence patello-femoral tracking.\(^41\) to \(^43\) Some studies claim to have shown no patellar complications\(^5\) because of appropriate rotational alignment when using navigation. A study by Siston et al.\(^44\) highlights the need for kinematic studies using computer-assisted techniques to improve our knowledge regarding perfect femoral component rotation. Also Yau et al.,\(^45\) using a cadaveric experiment, emphasise the challenge of achieving accurate femoral rotational alignment and the need for further refinement in navigation technology.

Navigation systems were found to be particularly useful for measurement of kinematic joint characteristics before and after surgery. Soft tissue laxity in flexion and extension can be determined using computer tools. Ligament balance and stability are essential to the immediate and long-term clinical success.\(^46\)

Navigation devices designed for universal implants are widely available but do not seem to offer the precise and user-friendly set-up we appreciate with specific implant-related systems. Navigation systems combined with individual implants seem to allow for less invasive instrumentation and thereby relatively shorter operating time with less bone and soft tissue damage. This appears to influence the number of thrombembolic events\(^47\) and blood loss.\(^24\) Chauhan et al.\(^48\) reported reduced loss of blood in navigated compared to conventional surgery. They attributed this finding to non-penetration of the femoral medullary canal and less invasive soft tissue management.

As with any new surgical tool, the debate regarding the learning curve for surgeons who would like to use navigation is controversial. Orthopaedic trainees are generally open and often enthusiastic about the idea of computer-assisted knee replacement surgery. Established surgeons might argue that they do not need it because they believe that they get sufficiently good results with conventional instruments. The experienced surgeon might also fear prolonged operating time. Research appears to challenge such statements.\(^1\) Planning and operating time do not appear to be increased significantly once the surgeon has passed the learning curve and image-free systems are being used.\(^20\) to \(^49\)

One study\(^1\) reports wound healing problems and early infection with computer-assisted knee surgery. It is suggested that navigation-guided procedures might cause more trauma to soft tissues. This might be the case with methods fixing trackers within the operation site and at the same time attempting to minimise the size of the incision. It is advisable to fix reference arrays far away from the surgical wound using percutaneous fixation and to flex the knee during insertion of the femoral trackers in order to avoid quadriceps damage.

The use of computer-assisted tools by orthopaedic surgeons requires individual instruction tailored to the technology used. Learning Centres and clinical input from colleagues experienced in the routine use of computer-assisted orthopaedic systems are paramount to success. Although clinical studies are difficult to conduct over a long period because conditions for investigation change frequently (system updates) it is recommended to feed back experiences to colleagues and manufacturers.

Electromagnetic tracking is a new key technology allowing miniature implantable trackers and overcoming line-of-sight restrictions of optical tracking. In the future, we should see navigation enabling new classes of less invasive and more functionally appropriate implants. The technologies that will permit this include new measurement systems for soft tissue management and conservative bone preparation tools. According to implant manufacturers automatic pre-operative planning and possibly auto-registration technologies should enable the surgeon to have a custom procedure kit that could greatly improve surgical productivity (Figs. 3 and 4).

Electromagnetic tracking technology eliminates line-of-sight issues associated with traditional optical systems. Electromagnetic tracking uses miniaturised computer tracking devices that can be positioned in vivo to facilitate in less invasive procedures. These tracking devices can for example be placed under the muscle during knee arthroplasty, causing no secondary trauma to the patient.

Leading joint replacement manufacturers have committed to investment in research aimed at the improvement of navigation systems. Navigation technology should enable reliable minimal access surgery and remove the outliers that mar the accuracy of the surgical procedure.

Currently, the cost/benefit ratio of computer-assisted surgery is abstract. If surgery is performed better the patient should benefit in having a better functional outcome and greater implant longevity. This, if realised, will produce material benefits to surgeons, patients and the community at large. There should be fewer revision procedures with all the associated savings.\(^49\)

Five years ago computer-assisted operations were criticised for additional surgical steps, which were time consuming and required more manpower. Recently systems

Figure 3 Electromagnetic technology (reproduced by kind permission of Zimmer\(^5\)): Tibial Alignment Guide with electromagnetic paddle in the slot of the tibial cut guide.
Outcomes should be the norm in our practice, however advanced technology with scientifically validated surgeons we are required to employ cost-effective methods, substantial orthopaedic productivity. As orthopaedic surgery does not satisfy the needs of a hospital with a hard- and software are cost intensive and one system alone refinement of surgical techniques.

Pre- and intra-operative data acquisition with post-operative flow is under constant update. Several processes to improve the recognition of tools, including the use of radio frequency intensifier. Modern systems are far smaller and more user-friendly. The graphical user interface and computer work-flow is under constant update. Several processes to improve the recognition of tools, including the use of radio frequency identification chips, are being implemented. Integration of pre- and intra-operative data acquisition with post-operative verification and clinical outcomes should lead to redefinition of surgical techniques.

One contentious point remains the financial expenditure. Hard- and software are cost intensive and one system alone usually does not satisfy the needs of a hospital with a substantial orthopaedic productivity. As orthopaedic surgeons we are required to employ cost-effective methods, however advanced technology with scientifically validated outcomes should be the norm in our practice.

**Practice points**

- A navigation system is a basic tool allowing us to understand and to modify individual knee joint biomechanics.
- Navigation systems complement mechanical instrumentation by the addition of measurements used to direct surgical tools and thus better align prosthetic components.
- Computer assistance aims to enhance accuracy in knee replacement surgery and may thereby improve long-term outcomes.

**Computer-assisted surgery facilitates both less invasive procedures and traditional surgical techniques.**

**Research directions**

- Data collected in computer-assisted knee arthroplasty will help to design future implants and determine most favourable alignment.
- Computer-assisted procedures should help to improve our knowledge regarding femoral component rotation and patellar tracking.
- Can auto-registration technologies be introduced to further reduce operating time.
- Will electromagnetic tracing become a reliable, user-friendly and cost-effective method replacing optical systems.

**References**


