Computer-Assisted Surgery: Pros and Cons

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Introduction

Computer navigation has evolved as an important method in orthopedic surgery for improving the accuracy and precision of surgical interventions. With the advent of the NDI digital camera, it has been possible to track dynamic reference bases or DRBs in "real time" on a computer screen. A DRB could be anything from a femur or tibia to an instrument, saw, or drill. With the advances pioneered by Dr. Stephane Lavallee in total knee replacement, the technology quickly took hold, primarily in Germany and other parts of Europe. Over the past 20 years, we have seen a steady growth in the proliferation of computer-assisted surgery, and we are now reaching the point of "better than not," which happens with all improvements where the newer technology exceeds previous capabilities. That is to suggest that we now have capabilities such as spine pedicle screw placement where the accepted method requires the newer technology. This has allowed for limited surgical approaches and performing operations where previously, large anatomical exposure was necessary for the guidance landmarks. The other exciting evolution over the past few years has been the proliferation of new technologies into the "space" of computer-assisted surgery. The technologies applied in total knee replacement are markedly streamlined with fewer "bells and whistles" and targeted applications. Patient-specific cutting guides are another example of simplicity, where the guide is created

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in advance by a vendor, utilizing preoperative CT or MRI scan data to model a cutting guide that is created as a custom device that is then applied intraoperative to the specific patient's geometry [1, 2]. Accelerometer-based guides offer similar accuracy to conventional computer navigation with a restricted menu of measurements [3]. Time efficiency has dramatically improved, even for the standard navigational systems, and this comes from the ability of the navigational software protocol to perform only those maneuvers that the surgeon is specifically requiring [4]. This is in great contrast to the early systems that provided a "standard" method of registration, basic surgical technique, and order of the surgical procedure.

Digital imaging has been a part of robotics and computer navigation from the outset and has been characterized by the need of a preoperative CT scan or MRI. Early on with the ROBODOC system, the digital image described the bone dimensions that could be used to create custom prosthetic implants and could guide the milling process of the bone down to submillimeter levels. The MAKO robotic system (Stryker, Inc., Mahwah, NJ) relies on preoperative CT DICOM files that are loaded into the MAKO computer at the time of surgery. Conventional anatomical registration methods are utilized to guide a haptic robot that directs the patient's bone preparation from a predetermined software protocol. These systems have been shown to have better precision than conventional instrumentation, but require a preoperative CT scan. With the availability of intraoperative 3D/CT such as the Medtronic O-arm, the surgeon will be able to capture the appropriate digital images at the time of surgery, eliminating the preoperative imaging for navigation [5].

Pros

In total knee replacement, early data on the use of these image-free optical tracking systems appeared positive with improved mechanical alignment, frontal and sagittal femoral axis alignment, and frontal tibial axis alignment. Multiple randomized control trials were able to demonstrate a statistically significant improvement in terms of placing the final mechanical alignment of the knee within 3° of the ideal mechanical axis [6–20]. We note that 93 % of the overall cases from these studies reach this level of precision with computer navigation compared to 74 % where conventional methods are used (Table 1). Zhang et al. performed a comparison study with bilateral total knees showing that conventional technique resulted in 28 % outside of the 3° mechanical outlier with no cases outlying in the navigation group [21]. Several meta-analyses have shown the advantage of computer-assisted surgery over conventional techniques for component alignment, blood loss, the Knee Society and WOMAC Scores, and a tendency for fewer overall adverse events [22–25]. Until recently, outcome data has not been able to demonstrate significant improvements in overall revision rates and general outcomes. However, a review of a large national total knee registry was able to show statistical improvements in the occurrence of implant loosening and osteolysis with the use of computer navigation [26].

Blood loss has been significantly reduced with the use of computer navigation and avoidance of intramedullary rods [27–29]. Kalairajah et al. were able to reduce the mean blood loss from 1747 ccs to 1351 ccs by using the pin-placed trackers instead of intramedullary-guided femur and tibia jigs which was a significant difference in 60 patients [30]. McConnell et al. similarly showed the reduction of mean blood loss from 1362 ccs to 1137 ccs with an even larger study including 130 patients [31]. A number of studies have been able to demonstrate early improvements in functional outcome with computer assisted over conventional [32, 33]. Gothesien et al. showed that the Knee Injury and Osteoarthritis Outcome Score was significantly better for sports and symptoms categories at 1-year follow-up [34]. Hoffart et al. found that navigation resulted in better mean Knee Society Scores ($p = 0.008$) compared to conventional instruments at 5-year follow-up [35].

Heyse et al. demonstrated the potential of preoperative digital registration with the creation of patient-specific cutting blocks [1]. He was able to show that the outliers of greater than 3° from the

Table 1 Clinical studies that compare the ability of conventional manual surgical techniques with computer navigation for placing the limb alignment within +/−3° of the mechanical axis of the lower extremity

Author	N	Navigated	Conventional	% Diff.
Haaker et al. [55]	100	**96 %**	**75 %**	**21 %**
Sparmann et al. [56]	120	**98 %**	**78 %**	**20 %**
Victor et al. [57]	50	**100 %**	**74 %**	**27 %**
Jenny et al. [11]	235	**97 %**	**74 %**	**23 %**
Jenny et al. [12]	30,30	**83 %**	**70 %**	**17 %**
Kim et al. [14]	69, 78	**78 %**	**58 %**	**20 %**
Perlick et al. [16]	40	**93 %**	**75 %**	**28 %**
Song et al. [19]	47, 50	**96 %**	**76 %**	**20 %**
Bathis et al. [58]	160	**96 %**	**78 %**	**18 %**
Perlick et al. [16]	50	**92 %**	**72 %**	**20 %**
Hart et al. [9]	60	**88 %**	**70 %**	**18 %**
Anderson et al. [59]	116, 51	**95 %**	**84 %**	**11 %**
		93 % (average)	**74 % ($P < 0.001$)**	**20 %**

neutral TEA axis using MRI for femoral component rotation were reduced from 22.9 % with conventional instrumentation and direct resection anatomical references to 2.2 % with patient-specific guides. The ability to assess axial images from preoperative MRI and computed tomography scans clearly exceeds the ability to pick visual landmarks in the intraoperative setting [36, 37]. Tibial rotation alignment of the tibial tray can normally be quite difficult even with navigation of the AP axis of the tibia or other landmarks such as the medial 1/3 of tibial tubercle. Numerous authors have used CT images to assess these landmarks postoperatively. Roper et al. were able to show interobserver reliability of 0.9 for assessing the position of the medial one-third of the tibial tubercle in relation to the tibial tray postoperative [38]. Kuriyama et al. have shown tibial tray position can be markedly improved using a CT-based navigation system [39]. Those authors used the intraoperative registration that was CT based to define the anterior/posterior axis of the tibia and then used a navigation-assisted placement of the tibial tray to demonstrate a precision of +/−3° for rotational alignment as compared to Akagi’s line. An important advantage for using CAS is the ability to carefully measure gap balance through the range of motion [40–42]. This measurement relies on the inherent precision of measuring the gap distances, and a recent study would suggest that this measure is clearly in the submillimeter range. Walde et al. have used computer navigation to assist the process of femoral rotation determination, noting that the best results were obtained using a tenor ligament balancing method [43]. They found that using direct measured resection referencing, the resulting femoral rotation varied from 12° of internal rotation to 15° of external rotation. Using tensors with ligament balancing, this was reduced to 3° of internal rotation to 2.5° of external rotation. Hino et al. found significant mid-flexion laxity when measuring the gaps at 10° intervals from 0° to 90° of flexion [44]. This laxity was not apparent at 0° and 90° and was found to be exaggerated in the posterior-stabilized techniques over the posterior cruciate retaining total knees. A number of studies have shown the ability of CAS to improve outcomes by aiding the surgeon in the ligament release and balancing methods.

Several authors have studied the ability of the computer to capture intraoperative kinematic data, with passive range of motion of the knee before and after prosthesis placement [45–48]. It is likely that this data could be analyzed with comparison to intraoperative CT data [37]. This may offer some predictive pre-implant scenarios where the surgeon may optimize various choices of the bone resection steps and even choices of prosthetic geometry. Siston et al. suggested that collecting this type of data could be combined with direct referencing of femur for improved determination of femoral component rotation. Matziolis et al. used navigation to calculate the flexion axis through the range of motion and with the help of a tensor during the assessment and noted that the measured axis more correctly paralleled the surgical epicondylar axis as compared to direct referenced cuts using the transepicondylar axis or Whiteside's line [46]. Several authors have been able to demonstrate the ability of computer navigation to guide implant placement in situations where conventional instruments are not applicable. This could include cases of extra-articular deformity and old traumatic cases where prior plates and rods impair the use of intramedullary guides [5, 33, 49–53]. I would consider these cases to be of higher complexity, and the surgeon must be fastidious and confident that referencing will be accurate. However, the capability to perform these techniques is obvious and enabling for the experienced surgeon (Fig. 1).

A recent publication from the Australian Orthopedic Association National Joint Replacement Registry has demonstrated that long-term revision rates in patients under the age of 65 have been significantly reduced by the use of computer navigation [26]. That study covered a period from 2003 to 2012 and considered over 44,000 navigated total knees of a cohort that represented 14 % of all total knees performed. The cumulative rate of revision at 9 years for younger patients was 7.8 % for conventional with a rate of 6.3 % with the use of navigation (hazard ratio: 1.38 [95 % CI = 1.13–1.67], $p = 0.001$). The most common cause of revision was implant loosening and chronic osteolysis. The conclusion was that computer navigation could be shown to improve implant survivorship in younger patients and could be shown to be cost-effective over the long term on this basis. In 2012, computer navigation has grown to include approximately 22 % of all cases in Australia.

Cons

There have been substantial detractors to the use of computer navigation and not without reasonable arguments. As noted, costs, technical complexity, and inefficiency have been major barriers for the entry of these systems into contemporary practice. Older surgeons, in general, have resisted the advent of the digital technology age, and this might include electronic health records, personal computers, video games, and, in our example, computers guiding the surgical intervention. On the other hand, this barrier has been reduced for younger surgeons who have grown up with video games and personal computers. However, Barrack et al. have fairly argued that the evidence to support the use of computer navigation in total knee replacement has been unconvincing [54]. Perhaps, a corollary is the fact that results of total knee replacement are in general satisfactory and the ability to consistently demonstrate incremental improvement is limited. The choice is not binary, allowing an equal argument for avoiding adoption.

Imageless navigation referencing suffers from inherent inaccuracy of the surgeon picking the correct proscribed anatomical reference points [7, 14, 19, 42]. Yau et al. compared the combined intraobserver error for image-free acquisition of reference landmarks during total knee arthroplasty finding that the maximum combined error for the coronal plane mechanical axis alignment was 1.32° [95, 96]. However, Davis et al. found that the mechanical axis of the femur in the coronal plane could vary from 5.2° valgus to 2.9° varus [15]. They point out that the clinical scenario must consider all possible errors, in this case the movement of the pelvis with hip registration that is assumed to be fixed in space. Other errors can arise from various steps during a total knee replacement, including, for example, the placement of pins for cutting blocks, actual variation of the sawcut with subsequent bone resection errors, and errors from cementing the implants into place. These errors can be additive, and the surgeon should be constantly evaluating these effects using a navigated surface block [14, 20]. The results for the assessment of the transepicondylar axis or the anterior/posterior axis of Whiteside are inconsistent as compared to mechanical axis alignment [34]. This most likely reflects the difficulty in reproducibly picking the epicondylar or AP axis landmarks.

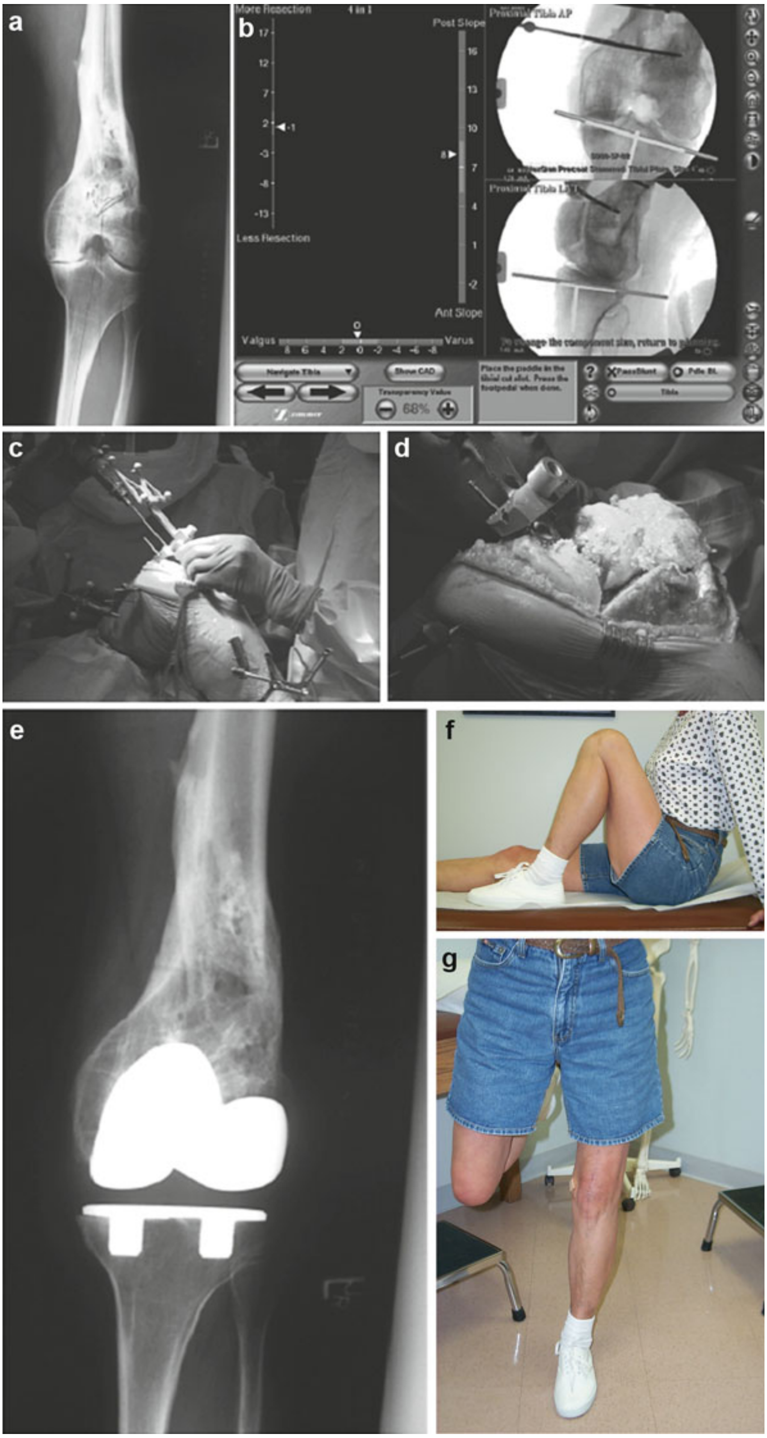

Fig. 1 56-year-old female who over 30 years ago had comminuted left femoral fracture treated with traction resulting in intramedullary canal obstruction and chronic deformity; (**a**) difficult total reconstruction in an old distal femoral fracture deformity. (**b**) Navigation of tibial cut shows planned cut to be 8° posterior slope, 1 mm of medial tibial plateau, and 0° to the mechanical axis. (**c**) Freehand navigation of the distal femoral cutting guide into the desired resection level and correct angle for the coronal and sagittal planes. (**d**) The distal femoral cut is made based on the freehand-navigated position of the cut guide. (**e**) The final radiograph shows the "perfect" position of the distal femoral cut, with a final mechanical axis measurement of 1° varus; (**f**) standing at 1-year post-op; (**g**) amount of postoperative flexion noted at 1 year

The problem with the AP axis for computer navigation referencing can easily be understood by the fact that distances for landmarking are very short. Slight errors in judgment can be off by several degrees. This contrast with the mechanical axis landmarking where an error of just 1 will require a point matching mistake of at least 5 mm. Yau et al. found that errors in the transepicondylar axis could be as high as 9° [96]. Davis et al. found the transepicondylar axis error could range from 11.1° of external to 6.3° of internal rotation [15]. Restrepo et al. found that the fixed posterior condylar axis reference could result in malalignment of more than 5 in 17 % of cases as compared to other rotational axes [69]. Siston et al. have shown that femoral rotation errors could easily exceed 5° in the hands of multiple surgeons with imageless navigation referencing [57]. For femoral and tibial prosthesis rotation errors, combining computer navigation and digital registration offers the potential for improving the precision, both of the implant position and ligament balancing techniques [80, 87, 90].

There are a number of anecdotal reports of stress fracture from pin placement for navigated trackers [3, 30, 38, 39, 43, 49, 51, 81]. These reports have demonstrated the larger 5 mm pins are problematic when placed bicortical in the shaft areas of the femur and tibia. Following the suggestion of Mihalko, the maximum pin thickness should be no more than 3 mm and probably should be placed unicortical in the tibia [55]. While this problem seems fairly limited, it would not appear to be isolated to extremely unlikely events.

Conclusion

We are in a transition period where an increasing amount of evidence supports the use of digital technologies for surgical image guidance. For minimally invasive applications, this guidance can be a strong asset as the exposures limit the precision of conventional instruments. As technology progresses, there will be more use of computed tomography and other imaging capabilities to improve registration and the surgeon's "view." We expect the younger generation to seek differentiation of skills with this method.

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