Navigation in Musculoskeletal Oncology: An Overview

Abstract

Navigation in surgery has increasingly become more commonplace. The use of this technological advancement has enabled ever more complex and detailed surgery to be performed to the benefit of surgeons and patients alike. This is particularly so when applying the use of navigation within the field of orthopedic oncology. The developments in computer processing power coupled with the improvements in scanning technologies have permitted the incorporation of navigational procedures into day-to-day practice. A comprehensive search of PubMed using the search terms "navigation", "orthopaedic" and "oncology" yielded 97 results. After filtering for English language papers, excluding spinal surgery and review articles, this resulted in 38 clinical studies and case reports. These were analyzed in detail by the authors (GM and JS) and the most relevant papers reviewed. We have sought to provide an overview of the main types of navigation systems currently available within orthopedic oncology and to assess some of the evidence behind its use.

Keywords: *Computer-assisted tumor surgery, navigation, pelvis, musculoskeletal tumors*
MeSH terms: *Tumors, pelvis, magnetic resonance imaging, computer assisted decision making*

Guy Vernon Morris[1], Jonathan D Stevenson[1], Scott Evans[1], Michael C Parry[1], Lee Jeys[1,2]

[1]The Oncology Department, The Royal Orthopaedic Hospital NHS Trust, Birmingham, West Midlands, [2]School of Health and Life Sciences, Aston University, Birmingham, United Kingdom

Introduction

On going technological advances have resulted in the development of new techniques and opportunities which have been incorporated into medical practice such as magnetic resonance imaging (MRI)-guided focused ultrasound therapy and proton beam therapy. The increased processing power of modern computers can permit the planning of complex surgical procedures such as deformity correction and tumor resection.[1] The production of computed tomography (CT) and MRI scanners with more detailed, accurate imaging capabilities coupled with the development of precise intraoperative navigation technology and equipment have led to the adoption and incorporation of new techniques within the field of orthopedics. Intraoperative navigation software has been utilized within medicine for a number of years.[2,3] Neurosurgery was first to adopt navigation into surgical practice, to map brain tumors preoperatively to determine their intracranial location and their surgical field providing more accuracy in their resections[4,5] As a result subsequent studies have shown improved margins in neurosurgical tumor resection.[6-8] Similarly, the adoption of navigation guided pedicle screw insertion has also been shown to reduce radiation exposure and screw malpositioning in spinal surgery.[9] The benefits of the technology in this setting are obvious; providing real-time visual feedback to the surgeon working with a very small margin for error. Further surgical specialties have since incorporated navigation systems into their practice including ENT and urology.[10,11] General orthopedics has also embraced the use of this new technology not only in trauma[12,13] but also in joint arthroplasty where its use has increased substantially.[14-20]

The development of navigation systems in oncological surgery has been termed 'computer assisted tumor surgery'. Within the field of musculoskeletal oncology surgery, navigation systems have played an important role particularly within pelvic surgery, limb reconstruction, and limb salvage. Hufner and Krettek independently described the use of navigation-aided resections of pelvic tumors in 2004.[2,3] While in 1999 Handels *et al*. described the virtual operation planning in orthopaedic surgery software which allowed the computer mapping of hip and pelvic tumors and the later construction of implantable allografts.[21-24] The aim of surgery is to achieve resection of the tumor with clear margins to achieve a reduction in the risk of local recurrence but without sacrificing

Address for correspondence:
Dr. Guy Vernon Morris,
The Oncology Unit, The Royal Orthopaedic Hospital NHS Trust, Bristol Road South,
Birmingham B31 2AP,
West Midlands, United Kingdom.
E-mail: guymorris@doctors.org.uk

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important structures and therefore function. Within the pelvis, access can be limited by anatomical constraints and, due to the extent of the tumor, intraosseous tumor margins can be difficult to appreciate. The role of navigation is to facilitate adequate surgical margins and safe resections, defined by a reduction in avoidable functional impairment. Preoperative imaging in the form of MRI, CT, and positron emission tomography-CT is performed to assess tumor placement, size, proximity to vital structures and extent of intraosseous disease. The location and involvement of vital structures then determine whether tumor resection with limb salvage is possible or whether amputation is the safest procedure. These imaging modalities can be fused to form a three-dimensional (3D) representation of the pelvis and tumor as described by Wong *et al*.[24,25] This can either be printed out in plastics or resins to form a physical model to assist in surgical preplanning (additive layer manufacturing), or it can be combined on the screen to form a visual representation. The benefit of this visual representation is that it allows detailed preoperative planning of osteotomies and their trajectories. This is of particular importance around the sacrum and posterior ilium as it can prevent the unnecessary resection of vital structures such as spinal nerve roots. Planned osteotomies can be marked on the 3D image or model to allow their visualization and preoperative rehearsal of their placement, which has been shown to improve surgical performance.[26] The degree of the intraosseous disease cannot be appreciated with the naked eye, and therefore, the use of the preoperative scanning coupled with the preoperative resection planning has been shown to reduce the incidence of involved margins at resection.[27-29]

There are two main types of navigation system currently in use in orthopedics; "image-based" and "image-less." The two predominant techniques utilizing computer navigation within musculoskeletal oncology are patient-specific instrumentation (PSI) or intraoperative navigation. An additional form of surgery utilizing navigation technology is augmented reality as described most recently by Cho *et al*.[30]

Intraoperative navigation within oncology most often is an "image-based" system where the imaging (preoperative scan) is required to supply the software with data. This is in contrast to "image-less" systems which are more widely used in arthroplasty surgery. In this system the software is supplied with information intraoperatively during the set-up process allowing the software to calculate a patient's anatomy by registering established bone landmarks such as the tibial tubercle or tibial plateau.[31] The software can then form an image of the patient's anatomy based on average appearances obtained from a large number of previous scans. The benefit of image-based systems is that it allows preoperative planning. In the technique of intraoperative navigation, the fusion of the preoperative CT and MRI images allows the tumor volume and extent to be mapped and color coded for easy identification on screen [Figures 1 and 2]. Navigation solely with MRI imaging has also been described as providing the added benefit of reduced radiation exposure to the patient.[32]

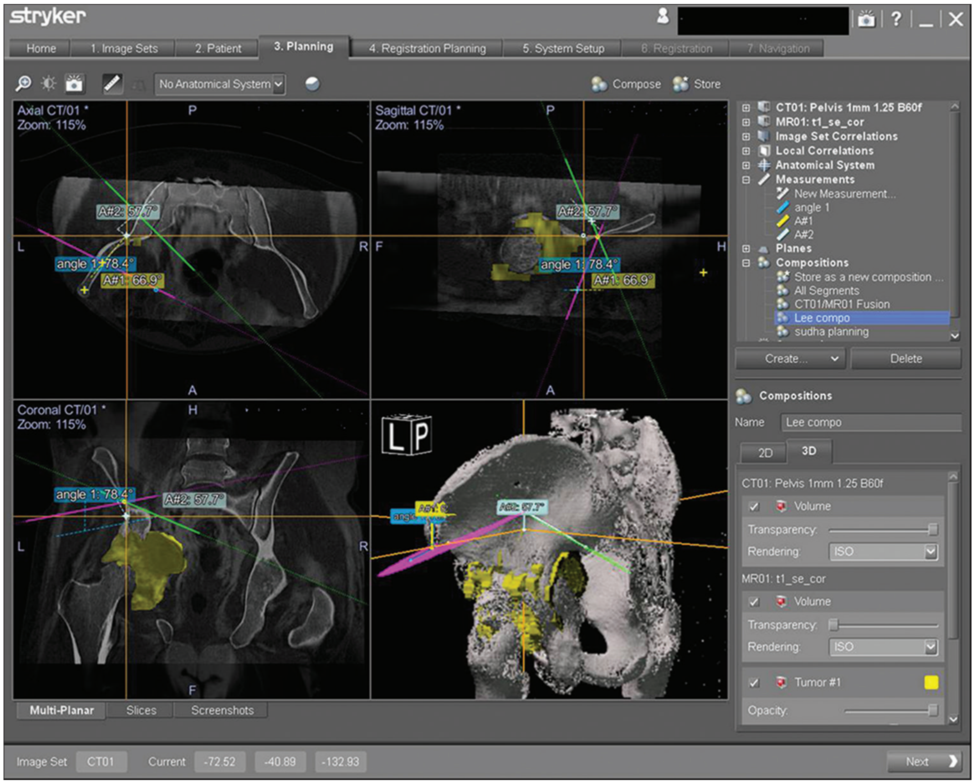

Figure 1: Preoperative resection templating on navigation software

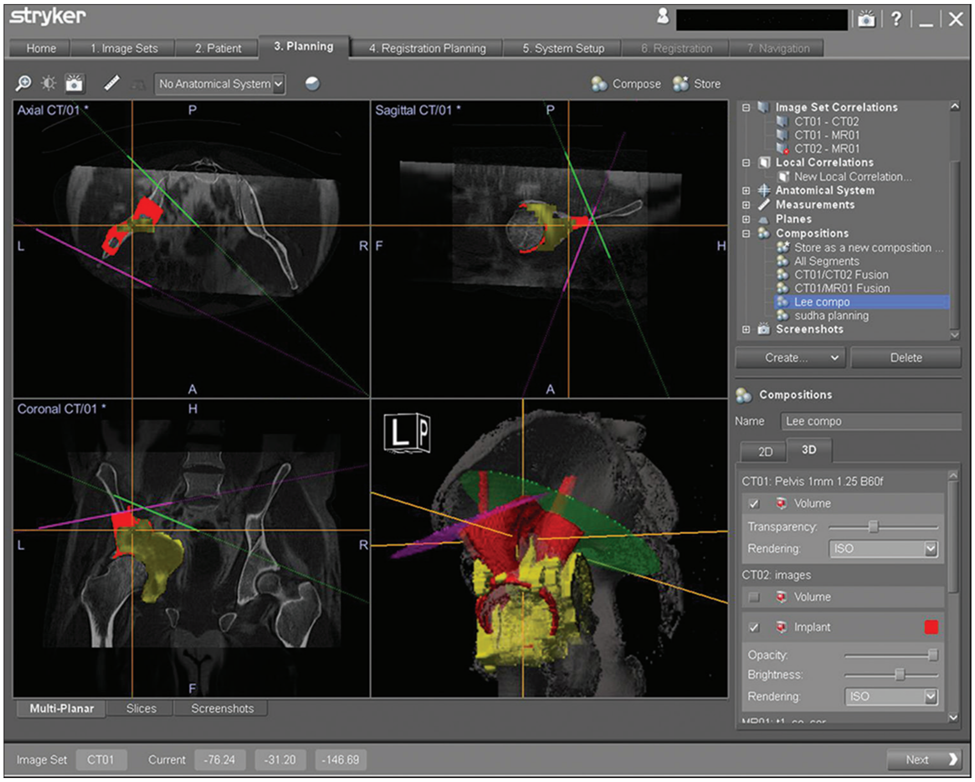

Figure 2: Color coded preoperative planning of resections (green and purple) with tumor (yellow) and computer aided design implant (red)

Unlike PSI navigation, the intraoperative navigation software requires matching to the patient on the operating table. This allows the software to assimilate the information obtained from the scans and map it to the patient. This is done by marking a series of reproducible and identifiable bony landmarks on the preoperative imaging. Such points would include the anterior inferior and superior iliac spine, posterior superior iliac spine, and iliac crest tubercle. Bone landmarks are chosen as soft tissue points can move and therefore reduce the navigation accuracy. A stereotactic camera emitting infra-red light on a mobile gantry picks up signals from reflective markers on a held instrument and then displays the locations of the instruments on a screen. Adequate surgical exposure is then obtained, and the bone landmarks are registered using a navigation probe [Figure 3]. The software is then able to match the patient's landmarks touched by the probe to those previously registered on the imaging. This registration process allows the software to establish a link between the real coordinates on the patient and the virtual coordinates within the imaging data. Further surface matching is then carried out to reduce the registration error to < 1 mm. This is done by marking 100 or more points across a bone surface in different locations. Once this registration has been completed, an accurate image of the fused CT/MRI is displayed with an exact position of a hand-held probe placed on the surface of the exposed bone. This permits real-time interactive assessment of the surgeons probe in space relative to the patient. It is possible to delineate distances between bone and soft tissue elements of the tumor without the risk of accidental intralesional resection. Instruments, such as osteotomes, can be calibrated to allow an accurate visualization of the exact position of the cutting blade of the instrument in relation to the osseous component of the tumor while performing a bone cut. The use of such devices has demonstrated accurate reproduction of the planned and actual margin achieved at resection [Figure 4].[33,34]

PSI requires preoperative scanning followed by production of a 3D physical model of the tumor and bony anatomy around which a precise cutting jig may be designed, also using ALM techniques. Using computer-aided design and computer-aided manufacturing (CAD-CAM) software the jig is developed to allow resection of the tumor to a predefined margin. The jig is pinned to the adjacent bone and acts as a guide for the osteotomy or bone saw. Laboratory studies have demonstrated reproducible margins when compared to the preoperative modeling without inadvertent intralesional resection.[35] This was however a saw bone study that does not have the soft tissue constraints that are present *in vivo*. However, Gouin *et al*. published their results of a study of eleven patients who underwent pelvic tumor resection and found that the bone resection margins were clear in all cases, with an average error in the resection margin of 0.8 mm.[36] The limitations of the use of PSI are apparent when the soft tissue extension of the tumor is taken into consideration. As the

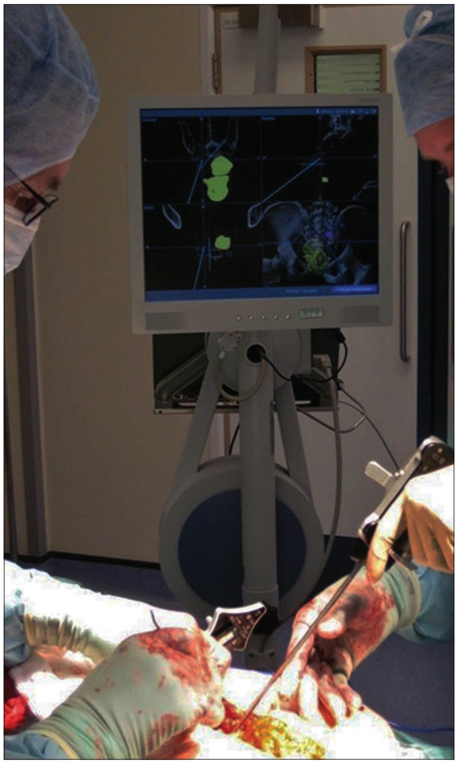

Figure 3: Intra-operative photograph demonstrating display screen and navigated probe and osteotome

Figure 4: Intra-operative photograph demonstrating display screen and navigated probe and osteotome

resection jig is applied for guidance of the bony resection, there is no aid to ensure an adequate soft tissue margin. As this is a static system, there is no real time imagery for intraoperative referencing as is seen with intraoperative navigation systems. Second, the time lag between the CT planning scan and the development of the patient-specific instruments may mean that the tumor has grown resulting in a mismatch between jigs and the tumor extension, which can result in intralesional resections. The cutting jigs are designed to fit to bony landmarks but can be difficult to fit accurately as a result of the soft tissue extension of the tumor or changes to the bony anatomy between the time of the scan and the time of surgery.[36] Equally, operator error remains. If jigs are not applied in the exact position determined by the preoperative plan, this may again lead to intralesional or inaccurate resections.[24]

One advantage of navigation-assisted surgery is a perceived reduction in operative time. Wong *et al*. reported on a cadaveric study which investigated the time taken for resection and resection accuracy between PSI and intraoperative navigation for pelvic tumor resection.[37] There was no statistical difference in the resection measurements between the two techniques, but there was a significant reduction in the time taken for the resection when using PSI. The anatomical challenges of surgery in the pelvis make accurate resections difficult. Cartiaux demonstrated that the probability of an experienced surgeon achieving a 10 mm surgical margin when working without navigation was 52%.[38] While it is known that surgical margins do not affect life-expectancy, margins do predict local.[39,40] Jeys *et al*. demonstrated a reduction in intralesional margins in tumors excised from the pelvis and sacrum using navigation-assisted surgery. They showed a reduction from 29% before the use of navigation to 8.7% following the introduction of intraoperative navigation.[41] This finding has been reproduced elsewhere. Young *et al*. demonstrated clear margins in all patients who underwent navigation assisted tumor resection not only from the pelvis but also of diaphyseal tumors.[28] Cho *et al*. also showed clear margins were achieved in all 18 patients included in their study assessing the application of intraoperative navigation for both pelvic and metaphyseal tumors.[42] Local recurrence occurred in only two patients both of whom had tumors excised from the pelvis.

Navigation has also been utilized in the field of limb reconstruction and limb salvage. Careful templating of tumors and soft tissues preoperatively can avoid unnecessary soft tissue resection and maintain function. Coupled with CAD-CAM software, allografts can be constructed that are tailor-made to fit into the precise resections that the navigation can provide [Figures 5 and 6]. These can be constructed for periarticular or diaphyseal tumors [Figures 7-10]. Li *et al*. have described very promising results in their use of navigation for performing complex juxta-articular resections in their limb salvage surgery with clear margins obtained in all cases both around the

Figure 5: Resection specimen and computer-aided design implant

Figure 6: Navigation and computer-aided design production allows higher degree of anatomical conformity between resection and implant

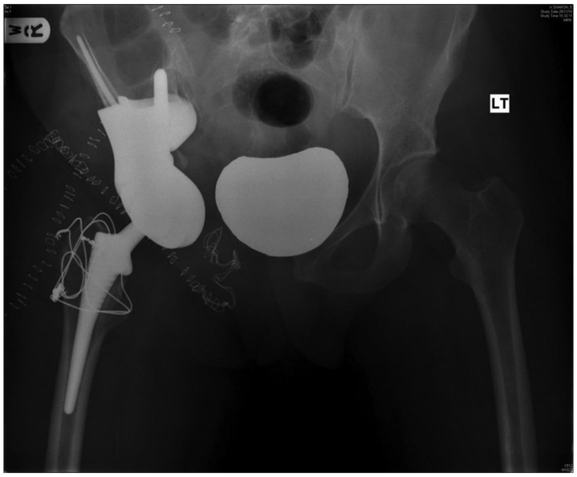

Figure 7: Postoperative radiograph of pelvis with both hips anteroposterior view showing implant *in situ*

Figure 8: Radiograph of pelvis with both hip joints anteroposterior view showing lytic lesion in left acetabulum

knee and the proximal humerus.[43-45] Furthermore, the use of navigation has shown to be useful in joint preservation surgery whereby tumors located in the metaphysis require accurate, precise resection to spare the joint or physis of the adjacent joint.[46,47] In a study of navigated chondrosarcoma excision around the knee Aponte-Tinao *et al*. compared the resected specimens with the preoperative planned resections and found a high level of accuracy between the two. The mean difference between the planned and actual resections was 2.43 mm.[48]

The complication rate of endoprosthetic reconstruction following pelvic resections is high,[49,50] in which the use of precise fitting allografts or custom implants is crucial to maintain implant longevity [Figures 11-14]. Nonunion in bulk allograft reconstruction has been reported as being as high as 27%, a study by Lall *et al*. demonstrated that the use of navigated resections can increase contact between resected bone and allograft compared to freehand technique.[51] This in theory should reduce the incidence of nonunion. Chen *et al*. have demonstrated a three to five-fold improvement in implant implantation precision compared when using navigation compared to conventional techniques.[52] Wu *et al*. describe the use of their "virtual bone bank" system to improve allograft selection time and matching accuracy. Donor bone allografts are scanned as DICOM images which were then reconstructed as 3D virtual models. A navigation system was then utilized to map the patient's bone defects and facilitate the accurate implantation of the allografts.[53] It is not only in the management of malignant tumors that navigation has been incorporated.[54] A study by Wong *et al*.[55] has demonstrated the use of CT based navigation with arthroscopic techniques in performing curettage of benign bone tumors

Figure 9: Magnetic resonance imaging sagittal cut showing extent of tumor mass

Figure 10: Postoperative radiograph of pelvis with both hip joints anteroposterior view showing insertion of custom implant following tumor resection

Figure 11: Radiograph of pelvis with both hip joints anteroposterior view showing large pelvic chondrosarcoma

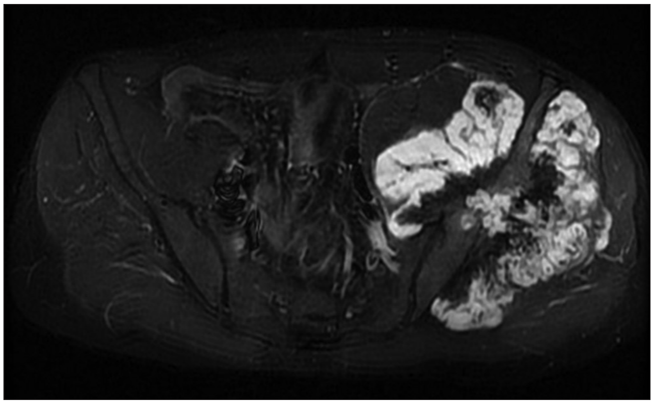

Figure 12: Magnetic resonance imaging scanning revealing extent of tumor spread

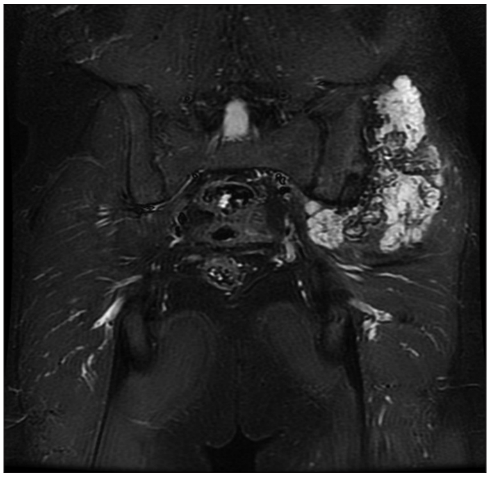

Figure 13: Magnetic resonance imaging showing sciatic notch involvement

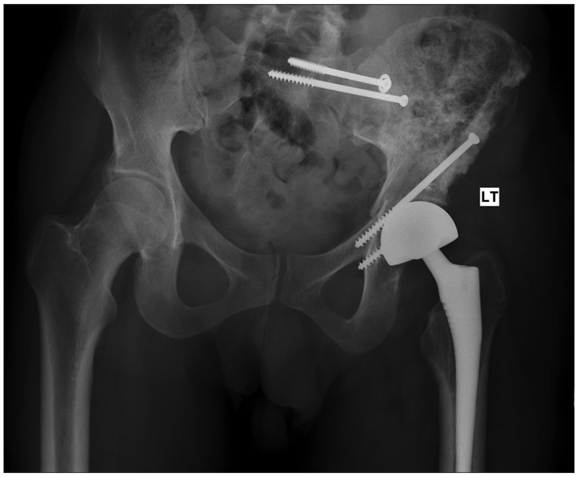

Figure 14: Postoperative radiograph of pelvis with both hip joints following navigated internal hemi-pelvectomy with irradiation and re-implantation

of the extremities. This small study notes the benefits of minimally invasive technique and the reduction in radiation dose through lack of continual intraoperative fluoroscopy. The margins of the tumor and tumor wall can also be better appreciated intraoperatively and thus ensure a more thorough debridement. These findings are reproduced by Lee *et al*. who conducted a study on 8 patients with deep benign bone tumors who underwent arthroscopic curettage with a navigated burr.[56]

The development of augmented reality surgery described by Cho *et al*.[30] offers an opportunity to simplify the image-patient registration process. In their study, they describe a system of navigation that relies on precise measurements of the affected bone along with the distances of the tumor margins to the bone ends. A computer generated bone model is then generated using a handheld tablet camera which takes images of the limb in various positions. A diagrammatic representation of a tumor in the bone is then generated by the software. The osteotomy through preplanned section of the bone is guided real-time monitoring with the software. They have shown an improvement in margins versus the use of conventional tumor excision techniques. However, this system can currently only be utilized in long bones and does not take into account any soft tissue tumor involvement.

There remain a number of limitations to the widespread adoption of navigation technology, particularly the use of intraoperative navigation. These include cost, increased preoperative planning time, the learning curve for development of surgical skills and the lack of evidence for long term outcome benefit. As with all technology, there is a time-dependent decrease in cost. Larger, higher volume hospitals are likely to find the acquisition of navigation equipment more affordable, especially if they can be utilized across specialties. With regards to operating time, Young found that the time for intraoperative registration was on average 30 minutes, but this decreased to 20 minutes after the fifth patient.[28] Aponte-Tinao *et al*. found similar results in a study of 69 patients that showed that navigation added an average of 35 minutes to the operating time.[57] In a meta-analysis of navigated knee replacements, it was found that the average increase in surgical time was 23% or 17 min.[58] In another study looking at navigated total knee arthroplasty, it was found that the operating time was significantly longer, but this leveled off after the first 30 procedures.[59] In contrast, Fafalli reported that the surgical operating time was reduced; although set-up time was not taken into account.[60]

The learning curve should be considered with all new technological developments and new techniques; interestingly, Fafalli did not show an appreciable difference in the learning curve of registration matching over time.

The longer-term benefits of the use of navigation in oncological surgery will only be able to be measured with time. It is only sensible to presume that surgical technologies that enhance patient safety, facilitate surgical accuracy and lead to improved patient care will become more commonplace in the future of musculoskeletal oncology surgery.

Summary Points

The navigation in musculoskeletal oncology has following advantages

(a) Optimal surgical margins and therefore reduced local recurrence. (b) Reduction in operative time. (c) Beneficial in complex pelvic or periarticular resections. (d) More accurate tumor resection and allograft implantation.

The disadvantages of navigation system are (a) Cost of equipment (b) Increase setup time (c) Learning curve.

Future potential

The future potentials of navigation system in musculoskeletal oncology are (a) Reduction in equipment costs (b) Smaller, more portable equipment (c) Potential incorporation of intraoperative robotics to further reduce surgical resection error.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent forms. In the form the patient(s) has/have given his/her/their consent for his/her/their images and other clinical information to be reported in the journal. The patients understand that their names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

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Conflicts of interest

There are no conflicts of interest.

References

1. Seide K, Faschingbauer M, Wenzl ME, Weinrich N, Juergens C. A hexapod robot external fixator for computer assisted fracture reduction and deformity correction. Int J Med Robot 2004;1:64-9.
2. Krettek C, Geerling J, Bastian L, Citak M, Rücker F, Kendoff D, *et al.* Computer aided tumor resection in the pelvis. Injury 2004;35 Suppl 1:S-A79-83.
3. Hufner T, Kfuri M, Galanski M, Bastian L, Loss MM, Pohlemann TM, *et al*. New indications for computer assisted surgery: Tumour resection in the pelvis. Clin Orthop Relat Res 2004;426:219-25.
4. Maldjian JA, Schulder M, Liu WC, Mun IK, Hirschorn D, Murthy R, *et al.* Intraoperative functional MRI using a real-time neurosurgical navigation system. J Comput Assist Tomogr 1997;21:910-2.
5. Kosugi Y, Watanabe E, Goto J, Watanabe T, Yoshimoto S, Takakura K, *et al.* An articulated neurosurgical navigation system using MRI and CT images. IEEE Trans Biomed Eng 1988;35:147-52.
6. Wirtz CR, Albert FK, Schwaderer M, Heuer C, Staubert A, Tronnier VM, *et al.* The benefit of neuronavigation for neurosurgery analyzed by its impact on glioblastoma surgery. Neurol Res 2000;22:354-60.
7. Sanai N, Berger MS. Glioma extent of resection and its impact on patient outcome. Neurosurgery 2008;62:753-64.

8. Kurimoto M, Hayashi N, Kamiyama H, Nagai S, Shibata T, Asahi T, *et al.* Impact of neuronavigation and image-guided extensive resection for adult patients with supratentorial malignant astrocytomas: A single-institution retrospective study. Minim Invasive Neurosurg 2004;47:278-83.
9. Kraus MD, Krischak G, Keppler P, Gebhard FT, Schuetz UH. Can computer-assisted surgery reduce the effective dose for spinal fusion and sacroiliac screw insertion? Clin Orthop Relat Res 2010;468:2419-29.
10. Vorbeck F, Cartellieri M, Ehrenberger K, Imhof H. Experiences in intraoperative computer-aided navigation in ENT sinus surgery with the aesculap navigation system. Comput Aided Surg 1998;3:306-11.
11. Rassweiler J, Rassweiler MC, Müller M, Kenngott H, Meinzer HP, Teber D, *et al.* Surgical navigation in urology: European perspective. Curr Opin Urol 2014;24:81-97.
12. Khoury A, Beyth S, Mosheiff R, Joskowicz L, Finkelstein J, Liebergall M. Computer-assisted orthopaedic fracture reduction: clinical evaluation of a second generation prototype. Curr Orthop Pract 2011;22:109-15.
13. Hamelinck HK, Haagmans M, Snoeren MM, Biert J, van Vugt AB, Frölke JP, *et al.* Safety of computer-assisted surgery for cannulated hip screws. Clin Orthop Relat Res 2007;455:241-5.
14. Ryan JA, Jamali AA, Bargar WL. Accuracy of computer navigation for acetabular component placement in THA. Clin Orthop Relat Res 2010;468:169-77.
15. Peterlein CD, Schofer MD, Fuchs-Winkelmann S, Scherf FG. Clinical outcome and quality of life after computer-assisted total knee arthroplasty: Results from a prospective, single-surgeon study and review of the literature. Chir Organi Mov 2009;93:115-22.
16. Petrella AJ, Stowe JQ, D'Lima DD, Rullkoetter PJ, Laz PJ. Computer-assisted versus manual alignment in THA: A probabilistic approach to range of motion. Clin Orthop Relat Res 2009;467:50-5.
17. Hoffart HE, Langenstein E, Vasak N. A prospective study comparing the functional outcome of computer-assisted and conventional total knee replacement. J Bone Joint Surg Br 2012;94:194-9.
18. Allen CL, Hooper GJ, Oram BJ, Wells JE. Does computer-assisted total knee arthroplasty improve the overall component position and patient function? Int Orthop 2014;38:251-7.
19. Kim YH, Kim JS, Choi Y, Kwon OR. Computer-assisted surgical navigation does not improve the alignment and orientation of the components in total knee arthroplasty. J Bone Joint Surg Am 2009;91:14-9.
20. Burnett RS, Barrack RL. Computer-assisted total knee arthroplasty is currently of no proven clinical benefit: A systematic review. Clin Orthop Relat Res 2013;471:264-76.
21. Handels H, Ehrhardt J, Plötz W, Pöppl SJ. Computer-assisted planning and simulation of hip operations using virtual three-dimensional models. Stud Health Technol Inform 1999;68:686-9.
22. Handels H, Ehrhardt J, Plötz W, Pöppl SJ. Virtual planning of hip operations and individual adaption of endoprostheses in orthopaedic surgery. Int J Med Inform 2000;58-59:21-8.
23. Handels H, Ehrhardt J, Plötz W, Pöppl SJ. Simulation of hip operations and design of custom-made endoprostheses using virtual reality techniques. Methods Inf Med 2001;40:74-7.
24. Wong KC, Kumta SM, Antonio GE, Tse LF. Image fusion for computer-assisted bone tumor surgery. Clin Orthop Relat Res 2008;466:2533-41.
25. Wong KC, Kumta SM, Leung KS, Ng KW, Ng EW, Lee KS, *et al.* Integration of CAD/CAM planning into computer assisted orthopaedic surgery. Comput Aided Surg 2010;15:65-74.
26. Arora S, Aggarwal R, Sirimanna P, Moran A, Grantcharov T, Kneebone R, *et al.* Mental practice enhances surgical technical skills: A randomized controlled study. Ann Surg 2011;253:265-70.
27. Laitinen MK, Parry MC, Albergo JI, Grimer RJ, Jeys LM. Is computer navigation when used in the surgery of iliosacral pelvic bone tumours safer for the patient? Bone Joint J 2017;99-B: 261-6.
28. Young PS, Bell SW, Mahendra A. The evolving role of computer-assisted navigation in musculoskeletal oncology. Bone Joint J 2015;97-B: 258-64.
29. Sternheim A, Daly M, Qiu J, Weersink R, Chan H, Jaffray D, *et al.* Navigated pelvic osteotomy and tumor resection: A study assessing the accuracy and reproducibility of resection planes in sawbones and cadavers. J Bone Joint Surg Am 2015;97:40-6.
30. Cho HS, Park YK, Gupta S, Yoon C, Han I, Kim HS, *et al.* Augmented reality in bone tumour resection: An experimental study. Bone Joint Res 2017;6:137-43.
31. Mezger U, Jendrewski C, Bartels M. Navigation in surgery. Langenbecks Arch Surg 2013;398:501-14.
32. Cho HS, Park IH, Jeon IH, Kim YG, Han I, Kim HS, *et al.* Direct application of MR images to computer-assisted bone tumor surgery. J Orthop Sci 2011;16:190-5.
33. Ritacco LE, Milano FE, Farfalli GL, Ayerza MA, Muscolo DL, Aponte-Tinao LA, *et al.* Accuracy of 3-D planning and navigation in bone tumor resection. Orthopedics 2013;36:e942-50.
34. Wong KC, Kumta SM. Joint-preserving tumor resection and reconstruction using image-guided computer navigation. Clin Orthop Relat Res 2013;471:762-73.
35. Cartiaux O, Banse X, Paul L, Francq BG, Aubin CÉ, Docquier PL, *et al.* Computer-assisted planning and navigation improves cutting accuracy during simulated bone tumor surgery of the pelvis. Comput Aided Surg 2013;18:19-26.
36. Gouin F, Paul L, Odri GA, Cartiaux O. Computer-assisted planning and patient-specific instruments for bone tumor resection within the pelvis: A Series of 11 patients. Sarcoma 2014;2014:842709.
37. Wong KC, Sze KY, Wong IO, Wong CM, Kumta SM. Patient-specific instrument can achieve same accuracy with less resection time than navigation assistance in periacetabular pelvic tumor surgery: A cadaveric study. Int J Comput Assist Radiol Surg 2016;11:307-16.
38. Cartiaux O, Docquier PL, Paul L, Francq BG, Cornu OH, Delloye C, *et al.* Surgical inaccuracy of tumor resection and reconstruction within the pelvis: An experimental study. Acta Orthop 2008;79:695-702.
39. Fuchs B, Hoekzema N, Larson DR, Inwards CY, Sim FH. Osteosarcoma of the pelvis: Outcome analysis of surgical treatment. Clin Orthop Relat Res 2009;467:510-8.
40. Ozaki T, Flege S, Kevric M, Lindner N, Maas R, Delling G, *et al.* Osteosarcoma of the pelvis: Experience of the cooperative osteosarcoma study group. J Clin Oncol 2003;21:334-41.
41. Jeys L, Matharu GS, Nandra RS, Grimer RJ. Can computer navigation-assisted surgery reduce the risk of an intralesional margin and reduce the rate of local recurrence in patients with a tumour of the pelvis or sacrum? Bone Joint J 2013;95-B: 1417-24.
42. Cho HS, Oh JH, Han I, Kim HS. The outcomes of navigation-assisted bone tumour surgery: Minimum three-year followup. J Bone Joint Surg Br 2012;94:1414-20.

43. Li J, Wang Z, Guo Z, Chen GJ, Yang M, Pei GX, *et al.* Irregular osteotomy in limb salvage for juxta-articular osteosarcoma under computer-assisted navigation. J Surg Oncol 2012;106:411-6.
44. Li J, Shi L, Chen GJ. Image navigation assisted joint-saving surgery for treatment of bone sarcoma around knee in skeletally immature patients. Surg Oncol 2014;23:132-9.
45. Li J, Wang Z, Guo Z, Chen GJ, Yang M, Pei GX, *et al.* Precise resection and biological reconstruction under navigation guidance for young patients with juxta-articular bone sarcoma in lower extremity: Preliminary report. J Pediatr Orthop 2014;34:101-8.
46. Cho HS, Oh JH, Han I, Kim HS. Joint-preserving limb salvage surgery under navigation guidance. J Surg Oncol 2009;100:227-32.
47. Fan H, Guo Z, Wang Z, Li J, Li X. Surgical technique: Unicondylar osteoallograft prosthesis composite in tumor limb salvage surgery. Clin Orthop Relat Res 2012;470:3577-86.
48. Aponte-Tinao LA, Ritacco LE, Ayerza MA, Muscolo DL, Farfalli GL. Multiplanar osteotomies guided by navigation in chondrosarcoma of the knee. Orthopedics 2013;36:e325-30.
49. Jaiswal PK, Aston WJ, Grimer RJ, Abudu A, Carter S, Blunn G, *et al.* Peri-acetabular resection and endoprosthetic reconstruction for tumours of the acetabulum. J Bone Joint Surg Br 2008;90:1222-7.
50. Campanacci D, Chacon S, Mondanelli N, Beltrami G, Scoccianti G, Caff G, *et al.* Pelvic massive allograft reconstruction after bone tumour resection. Int Orthop 2012;36:2529-36.
51. Lall A, Hohn E, Kim MY, Gorlick RG, Abraham JA, Geller DS, *et al.* Comparison of surface area across the allograft-host junction site using conventional and navigated osteotomy technique. Sarcoma 2012;2012:197540.
52. Chen X, Xu L, Wang Y, Hao Y, Wang L. Image-guided installation of 3D-printed patient-specific implant and its application in pelvic tumor resection and reconstruction surgery. Comput Methods Programs Biomed 2016;125:66-78.
53. Wu Z, Fu J, Wang Z, Li X, Li J, Pei Y, *et al.* Three-dimensional virtual bone bank system for selecting massive bone allograft in orthopaedic oncology. Int Orthop 2015;39:1151-8.
54. Kang HG, Cho CN, Kim KG. Percutaneous navigation surgery of osteoid osteoma of the femur neck. Minim Invasive Ther Allied Technol 2014;23:58-62.
55. Wong KC, Kumta SM, Tse LF, Ng EW, Lee KS. Navigation endoscopic assisted tumor (NEAT) surgery for benign bone tumors of the extremities. Comput Aided Surg 2010;15:32-9.
56. Lee HI, Shim JS, Jin HJ, Seo SW. Accuracy and limitations of computer-guided curettage of benign bone tumors. Comput Aided Surg 2012;17:56-68.
57. Aponte-Tinao L, Ritacco LE, Ayerza MA, Muscolo DL, Albergo JI, Farfalli GL, *et al.* Does intraoperative navigation assistance improve bone tumor resection and allograft reconstruction results? Clin Orthop Relat Res 2015;473:796-804.
58. Bauwens K, Matthes G, Wich M, Gebhard F, Hanson B, Ekkernkamp A, *et al.* Navigated total knee replacement. A meta-analysis. J Bone Joint Surg Am 2007;89:261-9.
59. Jenny JY, Miehlke RK, Giurea A. Learning curve in navigated total knee replacement. A multi-centre study comparing experienced and beginner centres. Knee 2008;15:80-4.
60. Farfalli GL, Albergo JI, Ritacco LE, Ayerza MA, Milano FE, Aponte-Tinao LA, *et al.* What is the expected learning curve in computer-assisted navigation for bone tumor resection? Clin Orthop Relat Res 2017;475:668-75.