Potential use of computer navigation in the treatment of primary benign and malignant tumors in children

Kevan Saidi

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Abstract The treatment of benign and malignant primary bone tumors has progressed over time from relatively simple practice to complex resection and reconstruction techniques. Recently, computer-assisted orthopaedic surgery (CAOS) has been used to assist surgeons to enhance surgical precision in order to achieve these goals. Initially, software developed for CT-based spinal applications was used to perform simple intraoperative point localization. With advances in technique and software design, oncology surgeons have now performed joint sparing complex multiplanar osteotomies using combined CT and MRI image data with precision and accuracy. The purpose of this paper is to provide a review of the clinical progress to date, the different types of navigation available, methods for error management, and limitations of CAOS in the treatment of pediatric benign and malignant primary bone tumors.

Keywords Pediatric musculoskeletal oncology · Computer assisted orthopaedic surgery · Navigation · Registration · Pediatrics · Musculoskeletal

Introduction

The treatment of primary tumors of bone in pediatric patients has dramatically evolved over the last few decades. Benign diseases that were once treated with large open procedures have begun to be treated with minimally invasive type surgical procedures [1]. The practice of treating

malignant diseases has progressed sequentially from simple amputations, to compartmental resections, to complex individualized resections involving specialized reconstruction techniques [2]. With this evolution in treatment, the complexity of preoperative planning and intraoperative technical demands that are placed on treating surgeons has dramatically increased. Obtaining successful results is dependant on both surgical expertise and anatomical spatial perception.

Similar progress and demands have grown in the fields of neurosurgery and maxillofacial surgery. Over the last two decades, this growth has resulted in the development and use of intraoperative computer assistance in order to improve surgical accuracy. An important example of these advancements in spinal surgery was demonstrated in a recent meta-analysis of 43 studies that revealed significantly less pedicle violation during spinal screw placement using computer versus traditional fluoroscopic assistance [3].

Initially, orthopaedic oncology surgeons turned to computer assisted orthopaedic surgery (CAOS) due to the inherent complexity of treating pelvic tumors. Cartiaux et al. demonstrated that even in an ideal surgical situation, with four experienced surgeons operating on plastic pelvic models with complete visualization and accessibility to bone surfaces, the probability of achieving a good surgical margin was only 52% (95% CI: 37–67%). In addition, reconstruction correlations between host-graft junction parameters were found to be poor [4]. A subsequent geometrical model study by Cartiaux et al. demonstrated that improvements in cutting accuracy could be achieved when CAOS was integrated into a freehand bone-cutting process [5].

The potential for enhanced surgical precision has been the main impetus for surgeons to begin developing CAOS for benign and malignant bone tumors. In addition, the potential benefits of CAOS in a pediatric population are evident when the importance of physeal sparing procedures is considered

K. Saidi (✉)
Department of Surgery, Division of Orthopaedic Surgery,
Health Sciences North, Northern Ontario School of Medicine,
2120 Regent Street South, Unit 2,
Sudbury, ON, Canada P3E3Z9
e-mail: ksaidi@hsnsudbury.ca

[6, 7]. An understanding of the principles of CAOS, knowledge of recent clinical progress, and appraisal of potentials for errors are all required in order for pediatric orthopaedic surgeons to take an active role in improving, validating, and developing pediatric CAOS. This review aims to provide an introduction to CAOS in order to advance the treatment of pediatric benign and malignant bone disease.

CAOS fundamentals

Workflow

Computer assisted surgery provides a surgeon with a real time, three-dimensional (3D) digital map of an instrument's position within a patient's anatomy in order to improve a surgeon's spatial accuracy. A simple but commonly used analogy is that of a ground-positioning satellite system (GPS) that provides a driver's car location on a digital city map [8].

The process of obtaining such a digital patient map with immediate surgical feedback involves a multiple step process that has been described as a CAOS workflow. Three-dimensional volumetric image data (MRI, CT) of the patient is first acquired to act as the digital map. With the use of computer rendering, the digital tumor can be highlighted and separated from normal tissue in order to aid with visualization. Using the highlighted image data sets allows a preoperative plan to be created that is used as a template to perform the surgeon's intended action. Intraoperatively, a navigating device is then used to localize the patient and track the position of operating room instruments. Next, the digital map is matched to the patient through a process known as registration, which creates an anatomical relationship between the patient and the virtual 3D map. The surgeon then validates the registration in order to ensure that an accurate matching has occurred. Finally, the position of surgical instruments is then transferred into the digital map in order to carry out the preoperative plan. When these tools are in the correct anatomical location and position, the surgeon is given immediate feedback by the computer to assist in carrying out the surgical plan.

Methods of navigation

In orthopaedic oncology, only image-based navigation systems that require preoperative image data are used, since patient-specific surgical planning is required. These platforms typically consist of a stereoscopic optical tracking system; positioning sensors that are placed on the patient, instruments, and intraoperative imaging devices; a computer processing unit; and a monitor to display virtual information. Optical tracking, which works through either active infrared emitting diodes or passive infrared light-reflecting

spheres, has been preferred over electromagnetic tracking due to higher accuracy and reliability [9]. Key determinants of success include both a direct line of site between the tracking system, instruments, and patient, and the maintenance of absolute stability of tracking devices that are fixed to the instruments and the patient [10•].

A number of platforms have been developed and used with cranial and spinal specific applications. Initially, the limitations of the platforms were accommodated through the placement of multiple virtual pedicle screws in order to guide surgeons during their resection planes. Later, navigation software modifications and the use of separate post processing software were used for planning, MRI–CT image fusion, and tumor segmentation. Recently, a dedicated orthopaedic oncology platform has been developed (OrthoMap 3D, Stryker Orthopaedics, Mahwah, NJ, USA) that allows users to perform image fusion between imaging data sets, tumor segmentation and volume rendering, and preoperative paired point and planar surgical planning. No system currently incorporates custom prosthesis computer aided design (CAD) into their interface, and if required, this process still needs to be performed on separate software.

The current platforms register patient to image data through rigid body transformations [11]. This technique is dependent on the fact that bone is a rigid and nondeformable structure and that the relationship between points is maintained on imaging and on the patient. Rigid body transformations fail when the structural arrangement of the bone is altered. For this reason, only single bones are navigated [8] and registered, and surgeons must consider the effects on their registrations when multiple osteotomies are to be performed.

Data acquisition

High resolution imaging is used to act as a virtual map of the patient during CAOS. The higher the image volume resolution, the more precise a registration can be performed. Resolution is determined based on the size of the operative area, the size of the tumor, and most importantly, the size of the anatomical points of interest that are to be used for matching. If the resolution is less than the intended object of interest, it may be lost in the volume data set.

Most investigators have recommended using CT volumetric data with a resolution of <1.5 mm [10••] for decreased volume averaging and motion artifact. Only one group has been successful using MRI data for their registrations, and this was performed with preoperatively implanted radio-opaque fiducial markers (FM), which can be found on both the patient and on imaging [12, 13].

When ordering preoperative imaging, surgeons should consider the most appropriate imaging modality for their intended surgery, whether the use of FMs will aid in their registration, and matching intraoperative patient positioning

during imaging to improve registration accuracy [10••]. Imaging with significant motion artifact must be repeated.

Preoperative planning

One of the most useful tools that navigation systems currently have is the ability to perform preoperative planning. Image data can be viewed in 3D to allow for planning of the surgical procedure, identification of important neurovascular structures, and choosing intended resection volumes or planes. Image data from different imaging modalities can be automatically overlapped. Through volume weighting, a surgeon can now view MRI data for soft tissue information, along with PET data for physiologic information, directly over CT data for bone information. The graphic user interface allows users to highlight the tumor, make annotations within the volumetric data, place 3D markers for referencing, and plan and place directional planes of reference for osteotomies. Planning can then be used intra-operatively in real time to execute the surgeon's intended action. Wong et al. have repeatedly emphasized the importance of preoperative planning in order to reach the intended surgical goal [14••, 7, 15, 16] and suggest that planning be performed on a large high definition monitor (*personal communication*).

Intraoperative calibration and registration

Although simple in its execution, it is essential that calibration be adequately performed before completing intraoperative registrations. First, a dynamic reference frame (DRF) with optical markers must be fixed to the patient securely, in most cases close to the intended area of resection. Calibration is subsequently performed with intended pointers, surgical instruments (diathermy, drills, saws), and intraoperative imaging devices that have trackers securely in place. Without accurately defining the geometry and shape of these objects with the coordinate system of the navigator, it is impossible to execute the intended surgical plan precisely.

A number of registration techniques currently exist that allow surgeons either to define points of registration or to allow the system to perform automatic registrations. Specifically, they can be grouped into feature-based or image-based rigid body registrations. In both instances, the patient is registered to 3D image data that is acquired preoperatively.

Three-dimensional feature-based registrations can be performed in two ways. The first invasive method is to use preoperatively placed FMs. Paired point (PP) matching subsequently occurs through the localization and pairing of these markers. The benefit of this approach is that it ensures the most accurate matching while the drawbacks include the morbidity (infection, discomfort) and time associated with a separate procedure [17]. The second noninvasive method is to use anatomical points that can be found by the surgeon on

imaging and on the patient to perform paired-point registrations. In both cases, a minimum of three PPs are required, but error has been found to decrease significantly when more than four PPs are used to perform a registration [10••]. The accuracy of the surgeon-defined PP matching is dependent on the surgeon's ability to identify pairs on the imaging volume data set and on the patient precisely. A significant drawback to this method is that it is time consuming and that it must be performed in the preoperative planning stage. The surgeon must choose and mark anatomical points in the imaging data set that are easily accessible or are in the surgical field, are around the tumor, and are noncollinear (not in the same 3D plane). Currently, no study has been performed to determine the optimal anatomical locations, based on tumor location, for matching in the pelvis, femur, or tibia.

Surface matching (SM) is subsequently performed to improve the accuracy of feature based registration. The surgeon chooses more than 20 bone surface points to create a patient-based 3D surface that the navigation system, through a transformational algorithm, matches to the image volume [8]. SM is based on the assumption that only a small number of points digitized on the accessible bone surface describe the surface precisely [17]. A similarity algorithm measures the degree of correspondence between the points on the image-based and patient-based surfaces [17]. Improved matching occurs if a greater number of points are chosen and if more complex surfaces are recreated. For example, the complexity of pelvic anatomy allows SM to occur more accurately than the diaphysis of the femur, which has similar anatomy along its length.

Image-based registrations occur through the use of an intraoperative imaging device. These registrations can either be performed from calibrated 2D fluoroscopic orthogonal images or calibrated 3D intraoperative CT images. Once a DRF is placed on the patient, and intraoperative imaging is obtained, the system performs an automatic registration by matching features on both preoperative and intraoperative data sets. Most systems use an intensity-based registration method that matches the intraoperative image data with the preoperative image through a similarity algorithm [8, 18]. The potential benefits of this method include improved accuracy, speed, and decreased surgical exposure for registration [17]. Drawbacks include equipment and computational cost, additional x-ray exposure, and poor quality partial volumetric view of intraoperative images [18].

Verification

Once the intraoperative registration is performed, verification must be done to ensure that an accurate representation of a tool's position in the patient is identified correctly in the virtual map and is displayed on the navigation monitor. A visual check is performed by the surgeon by placing an

instrument on the patient's boney anatomy and seeing if the corresponding location on the image map is correct. Surgeons should consider this to be the most important step in determining the accuracy of their registration, as the error that is generated by the system can be misleading. CAOS should not proceed if the surgeon is not content with the accuracy of the registration.

Error

A thorough discussion regarding CAOS error is an extremely complex task and is beyond the scope of this article. In an in-depth review on CAOS accuracy, Phillips noted that errors can occur at every stage of navigation and that these errors are propagated as one progresses through the workflow [18]. In simplest terms, Phillips stated that the accuracy of most navigation systems should be, at most, 1 mm when targeting a single point and 1° when targeting a line or resection plane. When operator error is included, the accuracy of most systems is likely 2–4 mm for a targeted point and between 1 and 3° for a targeted trajectory [18].

Most authors have reported their registration accuracy based on the calculated navigation system reported error (SRE). Unfortunately, this can be an under representation of the true error of the system. For this reason, an important distinction should be made between the SRE, which is defined as the root mean square error between chosen registered PPs, and the true registration error, which is the error between any measured anatomical target under the registration transformation and its corresponding location in the space of the virtual object [17]. The true registration error has been shown not to be uniform over the patient volume and is dependent on the distribution of the chosen PPs and the relationship of the tumor to the PPs [10•]. Error has been shown to decrease where the distribution of chosen PPs is highest and to increase as one moves away from chosen PPs [19–21]. It is for this reason that a visual verification of patient and image registration must always be performed.

A summary of the discussed suggestions for minimizing CAOS error is provided in Table 1.

Literature review

Although CAOS is exciting and quickly evolving, it is still in most respects in its infancy. Very little is published in either adult or pediatric orthopaedic tumor patients, and the majority of the case series are small, and patient followup is short.

CT based CAOS in malignant disease

Hüfner et al. (2004) were the first to describe using CAOS for resection of sacral tumors [22]. At the time, there was no dedicated oncology navigation platform, so the group used a

Spine module (Surgigate System: Medivision, Switzerland) that had been developed for pedicle screw insertion. Registration was completed in three patients, with two patients having Titanium pins placed to act as FMs. The authors then used navigated chisels to complete their sacral osteotomies and found a reported SRE of 1 mm.

Using the same technique, Krettek et al. (2004) subsequently described using CAOS for a sacral resection as well as a periacetabular resection that was reconstructed with a custom prosthesis [23]. They placed navigated K-wires in the direction of the planned resection line for their periacetabular resection and also used navigated chisels for the resection.

Reijnders et al. (2007) later described CAOS for resecting two iliac tumors using only SM of 20 points [24]. In both cases, they found a SRE of less than 2 mm and set-up and registration time of 1 h. The group suggested that implantation of FMs could reduce the difficulty of finding intraoperative landmarks for registration.

In a case report, Wong et al. (2007) described using CAOS to perform a periacetabular resection and reconstruction using Spine software (Stryker Navigation System: CT Spine Version 1.60) and a patient specific custom made prosthesis [15]. Their report was unique as they were the first to describe and emphasize preoperative planning as part of the CAOS workflow. Wong et al. used CAD software (MIMICS: Materialise's Interactive Medical Image Control System) to plan their osteotomy plane preoperatively, design and create a custom prosthesis, and fabricate a plaster model to practice and validate their technique. The group then performed the intraoperative registration using the preoperative CT with the preplanned osteotomy orientation embedded in the data set. SRE with four PPs was 2.3 mm and decreased to 0.3 mm with the addition of 50 SM points. A navigated diathermy was used to burn-in points that were joined for the osteotomy line, and the total time for navigation was 50 min.

Wong et al. (2007) expanded their experience in a case series of six patients where two resections were extra pelvic (proximal femur and proximal tibia) [25]. Using CAD software, they were the first to describe fusion of MRI and CT image data in order to delineate the tumor margins further. Mean time for preoperative planning was 3 h (range 1 to 6 h), the mean time for navigation was 28 min (range 13 to 50 min), and the mean SRE was 0.43 (range 0.35 to 0.63). They found that they were able to attach a navigated tracker to a drill and that their navigation times decreased with practice.

Wong et al. (2008) subsequently presented their largest series in 13 consecutive patients ranging in age from 6 to 80 years old (average age was 36) [16]. Four patients were of pediatric age, three of whom underwent a joint-saving resection with 1.5 to 2 cm of distal femoral epiphysis being preserved. MRI, CT, and PET imaging were initially coregistered manually at the start of the study (average

Table 1 Summary of suggestions for minimizing CAOS error (*Adapted from* Widmann et al. [10])**Preoperative imaging**

- Obtain high resolution imaging data with minimal patient movement
- Image patient in same orientation as intended procedure
- If required, Fiducial Markers should be securely placed, localizable, and have minimal image artifact

Preoperative planning

- Use large high definition monitor for planning
- Always choose >4 registration markers that are easily identifiable by the surgeon on both imaging and on the patient
- Registration markers must be broadly placed around resection area and not be within the same 3D coordinate plane
- If using different image modality data sets always visually check that coregistration are accurate before proceeding

Intraoperative set-up

- Ensure 30 min warm-up time for stereoscopic camera
- Place all tracking elements within the correct distance and centre of the stereoscopic camera field of view
- Ensure functional, stable, and readable placement of tracking elements on surgical tools and DRF
- Calibrate probes and instruments with care
- If using modality-based registration check calibration of CT gantry and tracking system and include areas of complex anatomy

Intraoperative registration

- Paired-Point Registration
 - Carefully match preoperative surgeon defined markers on imaging and the patient
 - Exclude markers with high individual errors
- Surface Registration
 - Ensure pointer is directly on bone surface
 - Paint broad areas with complex contour
 - Choose nonlinear planes, complex shapes, and > 20 points

Registration error

- System reported navigation errors should not be trusted
- Always check registration accuracy through visual check and do not proceed if surgeon is not confident with anatomical and virtual 3D matching

fusion time 48 min, range 30 to 80), while software improvements later allowed automatic registration (average fusion time 14 min, range 8 to 20 min) to less than 1 mm error. The navigation software allowed visualization of the different image data sets either individually, or they overlapped at different highlighted intensities, which the group felt allowed improvements at every stage of the workflow. The mean time for planning was 1.4 h (range 0.75 to 2.5 h), navigation was 24.3 min (range 13–40 min), and intraoperative accuracy or registration was 0.46 mm (range 0.35 to 0.68 mm). Additionally, the group was the first to validate CAOS to determine the accuracy of the intended planned resection. Seven resections were validated using either fusion of postoperative and preoperative CT images or by comparing the resection plane of resected specimens with that in surgical navigation. A match was also found in four patients between residual bone and custom prosthesis junction.

Cho et al. (2008) reported using K-wire FM registration to perform a complex sacral resection from an exclusively posterior approach while sparing the first and second sacral nerve roots and achieving an SRE of 1 mm [6]. The group expanded their experience in a subsequent paper (2009) where MRI and CT data were automatically registered using

fusion software (Vworks 5.0, Cybermed, Seoul, Korea) [26]. Registrations were performed using the CT data as the resolution was much higher and had been reduced in the MRI data during reformatting. In each of the three oncologic cases, SRE was <1 mm and osteotomies were performed with a navigated saw. Fiducial placement and preoperative planning took several hours, while navigation set-up and registration took an average of 30 min.

Wong et al. (2010) later described a method for integrating CAD planning using MIMICs into CAOS to perform the first multiplanar osteotomy for resection of a metaphyseal parosteal osteosarcoma and creation of a custom joint preserving prosthesis of the distal femur [7]. Through extensive preoperative planning, the group was able to plan, simulate, and perform a multiplanar resection that spared a portion of the medial condyle, the lateral collateral ligament, lateral condyle, cruciate ligaments, intercondylar notch, and blood supply to the distal segment. Previous reports had only involved resections along a single plane. The work flow was labor intensive as CT data format had to be converted to MIMICS data format. Resection plane surgical planning was then performed, and the surgical plan was then formatted back into CT data format in order to be fused to the

preoperative CT data using cranial navigation software (Stryker iNtellect Cranial Navigation Software, version 1.1, Stryker Navigation, Freiburg, Germany). The new fused data set was then used for virtual pedicle screw placement planning on a separate Spine navigation software (Stryker CT Spine Navigation, version 1.6, Stryker Navigation, Freiburg, Germany). The group found the initial learning curve to be steep and therefore suggested the process was only used for complex procedures at their institution.

Docquier et al. (2010) described the first CAOS case of combined periarticular tumor resection and allograft reconstruction [27]. Using a customized version of spinal software (Spine Application 1.4, Praxim, LaTronche, France) that allowed for target planes planning and implementation, the group performed a navigated tri-planer cut with a navigated saw on their patient and allograft to ensure precise resection and reconstruction. Preoperative planning using MRI to CT registration and allograft to patient registration was rehearsed first on a rapid prototyped model (Sirris, Leige, Belgium). During planning, the group determined the optimal location for DRE and that resection planes had to be moved back 1.5 mm to account for saw blade bone loss. They used 520 points for SM, resulting in an SRE of 0.42 mm.

Most recently, Cheong et al. (2011) presented one of the largest reported case series of their two-year institutional experience in 20 patients using the first dedicated CAOS tumor platform (OrthoMap 3D, Stryker Orthopaedics, Mahwah, NJ, USA) to perform resections in the pelvis, proximal and distal femur, and tibia [28]. The group felt that although surgical procedures took slightly longer to perform, navigation allowed them to improve their accuracy and precision of implant positioning and function, minimize limb length discrepancies, improve restoration of joint line and implant rotational alignment.

MRI based CAOS in malignant disease

Kim et al. (2010) described using MRI only image data for registrations as an alternate to CT-MRI fusion in order to minimize technical errors during registration and image fusion, as well as radiation exposure, to a 15 year-old girl with an osteosarcoma of her distal femur [12]. Three 1.5 mm extended resorbable pins (OrthoSorb, Depuy ACE Medical, Warsaw, IN, USA) were implanted beyond the resection area preoperatively and then imaged on a clinical MRI scanner. The pins did not cause image artifact and were easily localized on T1 and T2 images due to their low signal intensity [29]. A novel registration probe (FGS Biopsy Probe: Stryker, Kalamazoo, MI, USA) was pushed over the pins for accurate PP registration. The registration time took only 10 min, and the group was able to preserve the tumor free lateral femoral condyle, as well as the ACL, with which they fixed their osteoarticular allograft. Kim concluded that the

technique should be considered in epiphyseal or metaphyseal resections when PP matching landmarks might not be available due to possible tumor contamination. Cho et al. (2011) expanded on the groups experience in a case series involving six patient with an average age of 25 (range 18–52). Low SRE of 0.98 mm (range 0.4–1.7 mm) and short navigation times of 20 min (range 15 to 25) were found [13].

CAOS in benign disease

Athwal et al. (2004) first described the use of CAOS for the localization and excision of an osteoid osteoma [30], and later (2007) published their successful experience in 7 of 9 patients [31]. Two patients were of pediatric age, mean operative time was 88 min, and the mean time to discharge was 1 day.

Wong et al. (2010) recently published an elegant and novel percutaneous technique for successfully treating benign disease (3 Giant Cell Tumors, 1 Chondroblastoma, and 1 Chondromyxoid Fibroma), which they titled Navigation Endoscopic Assisted Tumor (NEAT) surgery [32]. They planned their portal sites preoperatively and estimated the volume of artificial bone graft required based on tumor volume. Intraoperative registration was performed using CT-Fluoroscopy matching technique. Tumors were visualized with an endoscope through one cortical window and resected through a second cortical window using a navigated high-speed bone burr. The authors found that the spatial (navigation-guided) reference enabled them to confirm that the entire lesion had been curetted as planned, while the endoscope (visual guidance) allowed them to identify residual tumor on the cavity walls. Preoperative planning took a mean of 31 min (range 20–45 min) with a mean procedural time of 144 min (range 120–165 min).

Minimally invasive CAOS in benign and malignant disease

Finally, Wu et al. (2011) reported CAOS to perform minimally invasive outpatient intralesional resections of periarticular and pelvic tumors [33]. Incision sizes were small (3 to 30 mm), blood loss was minimal (10 to 150 ml), and operative times were short (65 to 125 min). Intraoperative registration was performed by PP registration using novel intraoperative CT images (O-Arm Navigation System: Medtronic, Minneapolis, Minnesota). Two cases involved pediatric patients: a 17 year-old with a humeral epiphyseal chondroblastoma that was successfully treated, and a 16 year-old with an acetabular osteoid osteoma that later recurred requiring a second successful navigated procedure.

Limitations and future pediatric applications

A review of the literature demonstrates significant progression in the advancement of CAOS over the last decade. The

complexity, cost, and time required for successful implementation of CAOS has decreased, and several investigators have demonstrated proof of concept for adult and pediatric patients. However, even with the creation of a dedicated platform, most CAOS surgeons agree that regular use of navigation in treating benign and malignant bone disease is several years away. A number of limitations must first be overcome before wide acceptance of the technique occurs.

The first limitation is cost. Currently, navigation systems and intraoperative imaging devices are extremely expensive. The creation of shared platforms between orthopaedic, neurosurgery, and maxillofacial surgeons may aid in deferring some of the cost. The second limitation is time. Preoperative planning can be short for simple procedures, but as discussed, it can take many hours for complex resections in addition to time that is required if a custom prosthesis is to be developed in conjunction with surgical planning. Many groups have adopted a multidisciplinary approach to planning and implementation by involving biomedical engineers in order to decrease the time requirement for surgeons. The third limitation is education. Very few adult surgeons, and even fewer pediatric surgeons, have been exposed to CAOS. To date, only one group is providing an educational session on their experience with CAOS, and this presentation only occurs on an annual basis (Orthopaedic Learning Center, Chinese University of Hong Kong, Computer Assisted Tumor Surgery Workshop). In addition, at present, manufacturers do not allow open access to their preoperative planning software for surgeons to gain practice. Unless surgeons are permitted practice with the software, they will find it difficult to improve their efficiency for preoperative planning, and the CAOS will mostly only be used for simple resections. The fourth limitation is a lack of pediatric-specific research. A thorough investigation and understanding has yet to be performed to determine whether pediatric-specific issues, such as smaller patient size, potential for image motion artifact, or immature anatomical considerations including open physis and thickened periosteum, can play a part in affecting CAOS accuracy. The fifth limitation is the lack of evidence of oncologic benefit. The difficulty in obtaining an adequate number of patients to perform a randomized controlled trial will mean that it will be difficult to determine whether improved margins, local recurrence, and survival will result from CAOS. Finally, the sixth limitation involves a lack of tracker system validation and standardization of error reporting as pertains to orthopaedic oncology.

Conclusions

Even with the current limitations and lack of pediatric-specific research, CAOS has the potential to improve surgical precision in the treatment of benign and malignant bone disease in children. Using CAOS, investigators have demonstrated the

ability to treat benign disease through minimally-invasive techniques and to treat malignant disease in the pelvis, femur, and tibia safely, through patient-specific approaches. The future of pediatric CAOS seems promising if pediatric-specific training, clinical investigation, and scientific research are undertaken.

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References

Papers of particular interest, published recently, have been highlighted as:

- Of importance
- Of major importance

1. Volkmer D, Sichlau M, Rapp TB. The use of radiofrequency ablation in the treatment of musculoskeletal tumors. *J Am Acad Orthop Surg*. 2009;17(12):737–43.
2. Springfield D. Surgery for MSK tumors: 1971–2011. *Skeletal Radiol*. 2011;40(9):1233–7.
3. Tian NF, Huang QS, Zhou P, et al. Pedicle screw insertion accuracy with different assisted methods: a systematic review and meta-analysis of comparative studies. *Eur Spine J*. 2011;20(6):846–59.
4. Cartiaux O, Docquier PL, Paul L, et al. Surgical inaccuracy of tumor resection and reconstruction within the pelvis: an experimental study. *Acta Orthop*. 2008;79(5):695–702.
5. Cartiaux O, Paul L, Docquier PL, et al. Computer-assisted and robot-assisted technologies to improve bone-cutting accuracy when integrated with a freehand process using an oscillating saw. *J Bone Joint Surg Am*. 2010;92(11):2076–82.
6. Cho HS, Kang HG, Kim HS, Han I. Computer-assisted sacral tumor resection. A case report. *J Bone Joint Surg Am*. 2008;90(7):1561–6.
7. Wong KC, Kumta SM, Leung KS, et al. Integration of CAD/CAM planning into computer assisted orthopaedic surgery. *Comput Aided Surg*. 2010;15(4–6):65–74.
8. Nolte LP, Beutler T. Basic principles of CAOS. *Injury*. 2004;35 Suppl 1:S-A6–16.
9. Schicho K, Figl M, Donat M, et al. Stability of miniature electromagnetic tracking systems. *Phys Med Biol*. 2005;50(9):2089–98.
10. •• Widmann G, Stoffner R, Bale R. Errors and error management in image-guided craniomaxillofacial surgery. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2009;107(5):701–15. *Very thorough review of the errors commonly encountered during computer assisted surgery as well as practical discussion for error management.*
11. Fehlberg S, Eulenstein S, Lange T, et al. Computer-assisted pelvic tumor resection: fields of application, limits, and perspectives. *Recent Results Cancer Res*. 2009;179:169–82.
12. Kim JH, Kang HG, Kim HS. MRI-guided navigation surgery with temporary implantable bone markers in limb salvage for sarcoma. *Clin Orthop Relat Res*. 2010;468(8):2211–7.
13. Cho HS, Park IH, Jeon IH, et al. Direct application of MR images to computer-assisted bone tumor surgery. *J Orthop Sci*. 2011;16(2):190–5.
14. •• Wong KC. A practical guide to computer assisted tumor surgery: CATS. Red Corporation Ltd.; 2010. *Institutions' review of their clinical experience, with detailed case based examples to guide surgeons through the CATS workflow.*

15. Wong KC, Kumta SM, Chiu KH, et al. Computer assisted pelvic tumor resection and reconstruction with a custom-made prosthesis using an innovative adaptation and its validation. *Comput Aided Surg.* 2007;12(4):225–32.
16. Wong KC, Kumta SM, Antonio GE, Tse LF. Image fusion for computer-assisted bone tumor surgery. *Clin Orthop Relat Res.* 2008;466(10):2533–41.
17. Zheng G, Kowal J, Gonzalezballester M, et al. (i) Registration techniques for computer navigation. *Curr Orthop.* 2007;21(3):170–9.
18. Phillips R. (ii) The accuracy of surgical navigation for orthopaedic surgery. *Curr Orthop.* 2007;21(3):180–92.
19. Fitzpatrick JM, West JB, Maurer Jr CR. Predicting error in rigid-body point-based registration. *IEEE Trans Med Imaging.* 1998;17(5):694–702.
20. West JB, Fitzpatrick JM, Toms SA, et al. Fiducial point placement and the accuracy of point-based, rigid body registration. *Neurosurgery.* 2001;48(4):810–6. discussion 6–7.
21. Mascott CR. In vivo accuracy of image guidance performed using optical tracking and optimized registration. *J Neurosurg.* 2006;105(4):561–7.
22. Hufner T, Kfuri Jr M, Galanski M, et al. New indications for computer-assisted surgery: tumor resection in the pelvis. *Clin Orthop Relat Res.* 2004;426:219–25.
23. Krettek C, Geerling J, Bastian L, et al. Computer aided tumor resection in the pelvis. *Injury.* 2004;35 Suppl 1:S-A79–83.
24. Reijnders K, Coppes MH, van Hulzen AL, et al. Image guided surgery: new technology for surgery of soft tissue and bone sarcomas. *Eur J Surg Oncol.* 2007;33(3):390–8.
25. Wong KC, Kumta SM, Chiu KH, et al. Precision tumour resection and reconstruction using image-guided computer navigation. *J Bone Joint Surg Br.* 2007;89(7):943–7.
26. Cho HS, Oh JH, Han I, Kim HS. Joint-preserving limb salvage surgery under navigation guidance. *J Surg Oncol.* 2009;100(3):227–32.
27. Docquier PL, Paul L, Cartiaux O, et al. Computer-assisted resection and reconstruction of pelvic tumor sarcoma. *Sarcoma.* 2010;2010:125162.
28. Cheong D, Letson GD. Computer-assisted navigation and musculoskeletal sarcoma surgery. *Cancer Control.* 2011;18(3):171–6.
29. Baidya KP, Ramakrishna S, Rahman M, Ritchie A. Quantitative radiographic analysis of fiber reinforced polymer composites. *J Biomater Appl.* 2001;15(3):279–89.
30. Athwal GS, Pichora DR, Ellis RE, Rudan JF. A computer-assisted guidance technique for the localization and excision of osteoid osteoma. *Orthopedics.* 2004;27(2):195–7.
31. Athwal GS, Sahajpal DT, Rudan JF, Ellis RE. Computer-assisted localization of osteoid osteoma: an initial experience. *Orthopedics.* 2007;30(3):222–6.
32. • Wong KC, Kumta SM, Tse LF, et al. Navigation Endoscopic Assisted Tumor (NEAT) surgery for benign bone tumors of the extremities. *Comput Aided Surg.* 2010;15(1–3):32–9. *Novel technique for combining computer assistance and arthroscopy for treating benign aggressive tumors.*
33. Wu K, Webber NP, Ward RA, et al. Intraoperative navigation for minimally invasive resection of periarticular and pelvic tumors. *Orthopedics.* 2011;34(5):372.