Computer-Assisted Orthopaedic Surgery: Introduction and Applications in Orthopaedic Oncology

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Abstract

Computer-assisted surgery is a rapidly expanding field that enables improved intra-operative accuracy compared to the freehand surgical techniques currently utilized. It has been researched and developed for a wide array of surgical fields including Orthopaedic Surgery, Otolaryngology, Craniomaxillofacial Surgery, Spinal Surgery, Neurosurgery and Urology. Its use in Orthopaedic Oncology dates back to 2004, with rapid developments that have led to the ability to accurately and reliably plan resection planes with safe oncologic margins around malignant bone tumors. The purpose of this article is to provide an introduction to the topic of computer-assisted surgery, and to give a perspective on the current state and the future developments of this technology in the subspecialty of Orthopaedic Oncology. Further, the article provides a brief overview of the local work that has been done in this field in Toronto as part of the Guided Therapeutics (GTx) group at University Health Network (UHN) and Mount Sinai Hospital.

Introduction

Computer-assisted surgery is a rapidly expanding field that enables improved intra-operative accuracy compared to the freehand surgical techniques currently utilized. It has been researched and developed for a wide array of surgical fields including Otolaryngology,[1-3] Craniomaxillofacial Surgery,[4,5] Spinal Surgery,[6,7] Neurosurgery[8-11] and Urology.[12-15] In the field of Orthopaedic Surgery, previous surgical applications include knee arthroplasty,[16,17] high tibial osteotomy,[18,19] peri-acetabular and pelvic osteotomies, [20-22] and trauma surgery.[23]

A more recent application of computer-assisted surgery is in the field of Orthopaedic Oncology for the resection of challenging bone tumours. This was first reported in 2004 by Hufner et al. for the resection of sacral tumours.[24] Initial work in the field of computer-assisted Orthopaedic Oncology involved the use of computer navigation systems that were originally developed for other surgical fields and applications. These navigation systems often used tools that navigated a point in space, such as a pointer, a drill or a burr tip, rather than a plane such as that created by an osteotome or an oscillating saw.[25] The more recent applications of this technology involve free-hand navigation of planes of resection. These new applications come with unique challenges that require specially developed solutions for this field.[26-28] As such, the ability to have a highly customizable software and hardware development system is of significant importance for the active research and developments needed in this field.

The purpose of this article is to provide an introduction to the topic of computer-assisted surgery, and to give a perspective on the current state and the future developments of this technology in the subspecialty of Orthopaedic Oncology. Further, the article provides a brief overview of the local work that has been done in this field in Toronto as part of the Guided Therapeutics (GTx) group at University Health Network (UHN) and Mount Sinai Hospital.

Fundamentals of Computer-Assisted Surgery

Computer-assisted surgery provides a real time 3D virtual map that guides the surgeon during the operation being performed. Surgical tools being utilized are placed in the virtual 3D environment to allow for improved spatial accuracy of surgical resections beyond that provided by traditional, freehand surgical techniques.

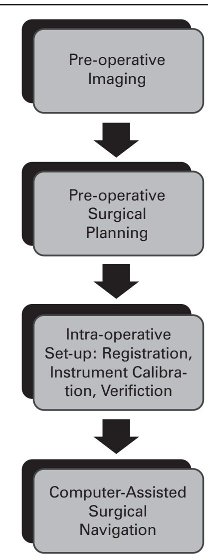

Figure 1. An overview of the typical workflow for computer-assisted surgical navigation in the operating room.

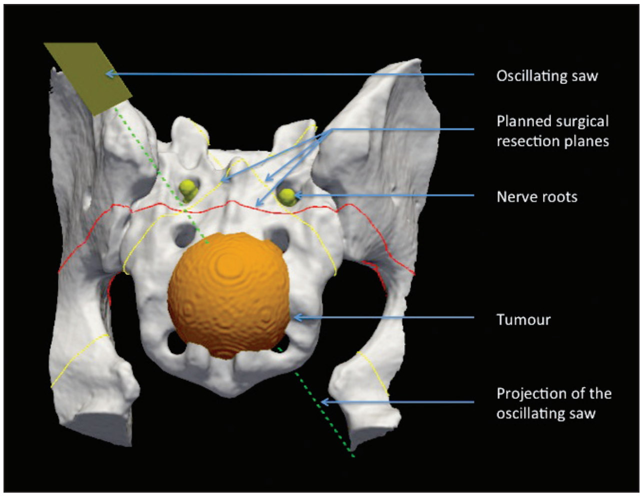

Figure 2. The CT of a sacral sawbone model with pre-operative planning highlighted, including the delineation of the tumour, sacral nerve roots, and surgical resection planes planned.

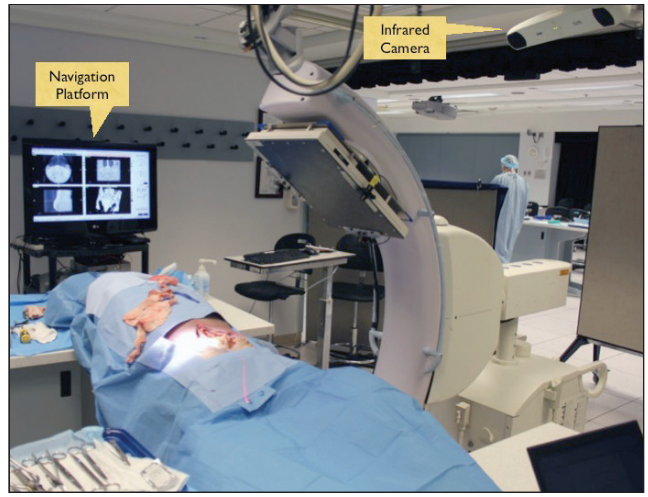

Figure 3. Optical camera navigation systems require the placement of an infrared camera in the direction of the surgical field. The camera needs to have a direct line-of-sight to the surgical instruments being tracked.

There are multiple steps involved in setting up and utilizing a navigation system for each patient. A general overview of this is shown in figure 1. First, pre-operative imaging is required to create the virtual 3D rendering of the anatomy that will be navigated. This is commonly in the form of a CT or an MRI of the patient. Through segmentation of this image, bones, tumours and other important structures can be identified and clearly demarcated for later navigation (Figure 2). Further, surgical plans such as planes of resection can be identified in the 3D imagery ahead of the surgical procedure. Of note, it is possible to delay this imaging to intra-operative period (using portable imaging hardware such as a C-arm CT), with subsequent planning of the surgical resection during the operation.

Intra-operatively, the first step is to register the navigation system for the given surgical environment and patient position. In order to allow for tracking of surgical instruments, the surgical environment needs to be co-registered with the virtual 3D image environment through direct association of a set of points or structures between the two worlds. Once this registration is complete, the surgeon needs to validate the registration through comparing the area navigated with a given instrument on the patient with the images being shown by the navigation software in the 3D virtual world. Furthermore, each instrument needs to be calibrated in order to ensure accuracy of all surgical tools within the navigation system.

Overall, this process results in the availability of accurate and real-time information about the position of each of the surgical instruments in the 3D virtual world.

Navigation System Hardware

In order to perform navigation, a hardware system needs to be used that is able to detect the position of equipment in an OR setting. There are 2 commonly used hardware technologies for surgical navigation: optical and electromagnetic. Each of these systems has a set of advantages that makes it the preferred tracking technology for a specific niche of applications. Optical tracking tools involve the use of an infrared camera with direct view of the surgical field (Figure 3). The benefits include a wider area of operation, higher accuracy, and lack of interference from electromagnetic devices that might already be within the surgical field.[29] However, the electromagnetic system has the added benefits of functioning without a direct line of sight, making it the tracking tool of choice for minimally invasive operations such as head and neck endoscopy.[30] In Orthopaedic Oncology, optical systems are most commonly used for surgical navigation.

Pre-operative Patient Images

The patient's pre-operative medical images play an important role in two aspects of the intra-operative navigation: they determine the accuracy of the registration that can be performed, and they indicate the types of information that will be available to the surgeon during the operation. For an accurate registration of the 3D virtual world with the real-life patient environment, high-resolution pre-operative images are required. It is recommended that a CT image with more than 1.5 mm resolution be used.[30] While CT reveals precise bony details, MRI is found to be superior in delineating the intraosseous and extraosseous extent of the tumour and provides crucial information with regards to tumour margins.[31] However, MRI images are difficult to utilize as the pre-operative images in navigation systems due to the typically lower resolutions that will hinder the registration process.

One solution to this problem is to perform a process known as image fusion. This involves the co-registration of the two imaging modalities, CT and MRI, in order to allow for information from both to be used within the navigation system. This will result in the added benefits of using the MRI image to perform tumour segmentation pre-operatively, and translating this information into the CT image for intra-operative registration and navigation in the higher resolution CT world.

Pre-operative Planning

Pre-op planning involves the identification of major structures within the pre-operative images of the patient. These include the critical neurovascular structures and tumour margins. Through identification and segmentation of these structures, appropriate surgical plans can be made and recorded within the pre-operative imagery. These surgical plans are then shown intra-operatively to the surgeon while the operation is being performed. In Orthopaedic Oncology, pre-operative plans commonly involve the creation of surgical resection planes. Intra-operatively, these resection planes are executed using oscillating saws and osteotomes. Pre-op planning has been shown to be an important step in ensuring that surgical goals are met with computer-assisted surgical navigation systems.[31-33]

Intra-Op Registration

There are two types of registration processes that can be utilized. These include freeform registration and registration using a reference tool. Both systems perform registration through the selection of paired points in the 3D image and the real-world patient environment. By selecting at least 3 pairs of points, the two worlds can be co-registered, allowing a point in the 3D OR environment to be translated to the corresponding point in the 3D virtual world. For higher accuracy, it is recommended that more than 4 pairs of points be selected in this registration process.[30]

The difference between freeform registration and registration using a reference tool is that the latter involves the placement of a fixed trackable tool on the patient. This allows for any patient movement that might occur intra-operatively to be accounted for in the registration and tracking of the other surgical equipment being used.

Registration between the paired points selected can be performed using two models: rigid and deformable models. Current navigation systems commonly use rigid model registration which assumes no changes in the shape and size of the structures being operated on.[30] This translates into the need for registration to be performed around a non-deformable object such as a single bone.[34] A major limitation of rigid registration is that once there is a separation of the bone through a resection, the navigation system no longer functions appropriately in one of the two bone segments created. This can be overcome by having trackers in each of the two segments, but becomes a significant challenge when resection leads to more than two segments. Deformable registration models do not have this inherent assumption about the rigidity of the structures being navigated.

Intra-op Instrument Calibration

Apart from registration, each surgical instrument needs to be calibrated individually to allow for accurate tracking of the instrument. Tracking of surgical instruments involves the attachment of a tracking device to the instrument. In case of optical systems, this involves the attachment of reflective spheres that can be seen by the infrared camera. For electromagnetic systems, an electromagnetic sensor is placed on the instrument.

The purpose of the calibration of instruments is to allow the tip of the instrument to be correctly located with respect to the attached tracking device. A means of streamlining this process is by using only pre-calibrated surgical equipment in the OR. This involves having surgical equipment sterilized with the tracking device pre-attached to the instrument. Although currently not practical, this optimization will be more feasible once computer-assisted surgical operations are more commonly performed.

Verification

An important step in setting up navigation systems is the verification process. After registration has been completed, the surgeon needs to verify the accuracy of the registration by enabling the tracking system and ensuring that specific points within the patient's body (such as important landmark structures) are translated accurately into the 3D virtual world.

Current State of Computer-Assisted Orthopaedic Oncology

With the advances in imaging modalities, Orthopaedic Surgeons are able to determine precisely the boundaries of primary bone tumours before performing surgical resections on patients.[35,36] However, previous literature has shown that even in ideal conditions, traditional tools and techniques substantially limit the reliability and reproducibility of executing pre-operative surgical plans during the operation, sometimes resulting in difficulty obtaining safe surgical margins around tumours.[37] This can particularly be true in areas with complex anatomy such as the pelvis and spine. As a result, cuts can be made into malignant bone tumors, leading to increased local recurrence and mortality rates[38-46] With pelvic osteosarcoma, obtaining marginal margins and intra-lesional margins have been associated with local recurrence rates of up to 70% and 92% respectively.[46] On the other hand, achieving adequate margins by resecting more tissue than is needed can lead to poor long-term functional outcomes.[47-52] It is thus of high importance to ensure the precise accuracy of cuts performed in Orthopaedic Oncology.

Computer assistance has been shown to be associated with improved bone cutting ability when treating bone tumours.[24,53-58] Although most previous papers have demonstrated tumour-free resections with computer-assisted surgery, a handful of studies have also shown the ability to achieve specific surgical margins for these patients.[26,55,56,59,60]

As previously mentioned, navigation systems in surgery often use tools that navigate a point in space, such as a pointer, a drill or a burr tip, rather than a plane that would be created by an osteotome or an oscillating saw.[25] Major advances have occurred since the first introduction of computer-assisted surgery in the field of Orthopaedic Oncology in 2004 by Hufner et al.[24] The more recent applications allow for free-hand navigation of a plane of resection, an important feature for resection of bone tumours. In the last decade, navigation systems have been used in the tracking of osteotomes,[61] chisels,[57] drills,[62,63] burrs,[54,64] and oscillating saws,[60,65,66] and have addressed some of the challenges specifically present in this subspecialty.

The first reported case of computer assistance in Orthopaedics Oncology involved the resection of sacral tumours using a navigation system that was originally developed for spinal surgery.[24] This study utilized CT as the imaging modality for registration and navigation. The same commercial system was utilized in two subsequent studies published in 2004 and 2007, with resections performed for peri-acetabular and iliac tumours respectively. [57,67] Wong et al. first emphasized the importance of pre-operative planning, utilizing a computer aided design (CAD) software to create custom made prosthesis to assist in performing navigated peri-acetabular resections .[62] The group went on to perform a series of resections involving the pelvis, proximal femur and proximal tibia, and was the first group to describe the use of MRI/CT fusion as a means of improving tumour margins.[58] In their subsequent study, Wong et al. achieved another first, validating the accuracy of producing the planned resection planes using a navigation system on 13 patients.[31]

Docquier et al. was the first group to report on the use of computer assistance in both the resection and the reconstruction of bone tumours.[68] The idea behind this is that through utilizing the same resection plans that were used for removing of the tumour, a similarly shaped cadaveric allograft can be created. The allograft would ideally fit perfectly into the area of the defect and have minimal gaps along the interface with the native bone.

With the advances in the resolution of MRI imagery and registration techniques, there have also been recent publications that performed registration and navigation using MRI images alone. Kim et al. performed computer-assisted surgical resection of an osteosarcoma of the distal femur of a 15 year old girl, opting to do an MRI-only study to minimize radiation exposure.[69] Cho et al. expanded on this technique, performing a case series on six patients using MRI images only.[70] The low error rates reported in these studies open the door for the possibility of reduced dependence on CT imagery for pre-operative planning and navigation in this patient population.

Local Developments in Computer-Assisted Orthopaedic Oncology

University Health Network and Mount Sinai Hospital are home to the Guided Therapeutics (GTx) program. The GTx program is focused on developing new image-guided technology for advanced therapeutics in surgery, interventional radiology and radiation medicine. The program coordinates the development of this technology through the creation of a shared clinical research space at the MaRS Discovery Tower.

All stages of this technology are performed with a single software package written in C++ and developed in-house using the VTK (Visual Toolkit; http://www.vtk.org/) and IGSTK (Image Guided Surgery Toolkit; http://www.igstk.org/) open source toolkits. The software package communicates directly with commercially available hardware tracking devices from NDI (Waterloo, Ontario).

Two types of instrument tracking are incorporated into this software package: optical tracking, and electromagnetic tracking. Optical tracking is performed using NDI's Polaris® Spectra® camera which overlooks the surgical field and detects, through infrared light, the reflective spheres (NDI Passive Spheres) placed on the surgical instruments being tracked. The electromagnetic tracking system utilizes NDI's Aurora® electromagnetic tracking system, and requires the placement of electromagnetic sensors on the surgical instruments. These sensors are directly connected, through a wire, to the main electromagnetic device.

The GTx group has worked extensively in the field of Otolaryngology, with dedicated applications for rigid and flexible endoscopy operations. Further, the technology involved in allowing the tracking of flexible endoscopes within the human body has been applied to the field of radiation therapy, enabling more accurate radiation treatments to be provided to patients suffering from cancer involving the mucosal lining of the esophagus. This has been performed through co-registration of endoscopy images with the pre-operative CT images of the patient, and the utilization of the tracking information obtained during endoscopy in order to improve the margins for radiation therapy provided.[71]

Although there had been extensive work in Otolaryngology and Radiation Therapy by this team, the utilization of this technology in the field of Orthopaedic Surgery locally has been much more recent. In 2006, two papers were published by the group describing the benefits of utilizing intra-operative CT imaging for treatment of tibial plateau fractures.[72,73]

Direct collaboration between the GTx team and the Orthopaedic Oncology group at Mount Sinai Hospital began in the year 2012. Through the use of the tools that were already extensively developed for other surgical applications, Sternheim et al. performed a series of cadaveric and Sawbones® (Pacific Research Laboratories, Vashon, WA) composite bone model resections using both computer-assisted and traditional surgical techniques.[60] Cuts were performed on three different tumour models (a peri-acetabular tumour, a sacral tumour, and an SI joint tumour) using pre-planned cutting planes (Figure 2). The conclusions made by the study were that navigated cuts were significantly more accurate than non-navigated cuts, and that a margin of 5 mm between the target tumour and the planned cut planes resulted in negative margins in more than 95% of the cuts.[60]

Currently, the team is actively working on addressing another challenging task in Orthopaedic Oncology: the ability to resect tumours involving a single cortex of a long bone and reconstructing the defects created using similarly cut cadaveric allograft. This is referred to as geometric resection. It is a procedure that has proven to be difficult without computer assistance, mainly due to the challenges of creating a precise fit for the resection gaps.[44,74]. A lack of precise fit leads to the existence of discrepancies in the junction between the host and the allograft, and can lead to increased risk of non-union and osteosynthesis failure. Based on our knowledge, only one group has previously investigated the process of computer-assisted resection and allograft reconstruction.[65]

Our goals are to address the main issues faced in our first local study of computer-assisted Orthopaedic Oncology. Through improving both the in-house hardware and software package, the aims of the study are to allow for a high-accuracy geometric resection module. One of the features already implemented into this navigation tool is the provision of real-time quantitative information to the surgeon about the pitch and the roll offsets of the surgical resection being performed compared to the pre-operative planned resection plane. This is very similar to the navigation tools used in the field of aeronautics. This, along will further advances in the pre- and intra-operative resection planning tools, will hopefully allow for a highly accurate and reliable geometric resection module in the coming months.

Limitations

The main limitations behind the use of computer-assisted surgical tools in the field of Orthopaedic Oncology include high equipment cost, and extensive pre-operative planning and intra-operative navigation time needed.

The first challenge with computer-assisted Orthopaedic Oncology is the high cost. Although the cost is projected to decrease as the number of centers purchasing such units increases, the current commonly used solution is to share the computer-assisted surgical tools between multiple surgical departments. An example of this is the sharing of navigation equipment between the Otolaryngology, Neurosurgery and Orthopaedic Surgery groups at various hospitals across North America. An advantage of the in-house navigation system being made by the GTx group in Toronto is that it allows for development of specialty-specific tools while maintaining a shared software and hardware system that can be easily used by multiple departments with the same hospital.

The second issue is the additional time that is needed to perform computer-assisted surgeries. Computer-assisted tumour resections require additional time pre-operatively for planning surgical resections, and intra-operatively for registration and active tracking of the instruments. Pre-planning time has been previously reported to be between 16 and 35 minutes per patient.[59] Navigating pre-planned cuts has been previously reported to be between 13 to 50 minutes per patient.[58] The in-house GTx system allows for full-customization of the navigation platform, permitting the engineers to identify time-consuming components of the navigation for each surgical discipline, and optimize the platform in order to reduce this overhead time.

Finally, computer-assisted surgeries in Orthopaedic Oncology face the general limitations that are present with surgical navigation. These include but are not limited to tracking error and line of sight challenges during surgery.

Conclusions

Computer-assisted Orthopaedic Surgery is a rapidly developing field with large clinical potential in the subspecialty of Orthopaedic Oncology. Through learning from prior works done in computer-assisted surgery in other fields, namely Otolaryngology and Neurosurgery, we are able to dramatically improve upon the already existing navigation tools being used in research and clinical practice in Orthopaedic Surgery. The Guided Therapeutics (GTx) team at University Health Network has developed an in-house computer navigation system that has previously been used for Otolaryngology and Radiation Oncology applications. By building upon this system and creating customized applications for Orthopaedic Oncology, we hope to address some of the main limitations in the adoption of this technology in this field.

Acknowledgments

We thank Dr. Amir Sternheim, Dr. Robert Weersink, Mike Daly and Jimmy Qiu for their assistance with the development of the in-house computer-assisted system presented in this work.

Conflicts of Interest

The author of this journal has been involved, and has received research stipends, from the Guided Therapeutics (GTx) group at University Health Network. The readers are advised to take this conflict of interest into consideration.

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