Technical Principles of Computer Assisted Orthopaedic Surgery

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Surgical navigation systems and medical robotic devices are increasingly being used during orthopaedic interventions. The aim of this article is to present the underlying technologies and concepts of these computer assisted orthopaedic surgery (CAOS) devices. Examples of pre-operative or intra-operative imaging modalities, of trackers for navigation systems, of different surgical robots, and of methods for registration as well as referencing are discussed. CAOS modules that have been realized for different surgical procedures will be presented and critically reviewed. Potential pitfalls that may occur with the use of this technology will be discussed.

Introduction

When surgeons started dissection of cadavers in order to broaden their knowledge on the interior of their patients' bodies, they could better understand and treat pathologies that were invisible from the exterior. More and more complex interventions could be carried out with increasing experience, in particular after the introduction of anesthesia by Horace Wells in 1844.

To minimize the damage to the surrounding tissue caused by an operation, tools were soon developed to execute a pre-operative planning as precisely as possible. Neurosurgery took on a leading role in this development, which may be explained by the sensitivity of the intra-cranial anatomy. Clarke and Horsley presented a "stereotactic apparatus" as early as the beginning of the last century (1). The device allowed location of a target within the brain that had previously been marked in an anatomical atlas (1). Stereotactic frames are nowadays common instruments during neurosurgical interventions (2). They are based on the same principles that were the foundation of Clarke and Horseley's construction.

For a long time orthopaedics declined the use of comparable systems, because frame-based surgery is obviously impractical for the treatment of the musculoskeletal system in most cases. Only in the last 15 years devices were developed that enable the orthopaedic surgeon to execute a pre-operative plan accurately during an operation. Two classes of apparatuses may be distinguished: Surgical navigation systems – precisely: surgical free-hand navigation systems – determine the spatial location of conventional instruments held in the surgeon's hand and provide positional feedback on a computer monitor in real-time (3). Such a system is a passive device that is used as an orientation aid, similar to a GPS satellite navigation system.

The second class consists of medical robots that autonomously carry out a defined step of an operation without any interaction by the surgeon (4,5). Although both classes do not seem to have much in common, they in fact represent quite similar derivatives of the general principle introduced by Clarke and Horsley more than 100 years ago.

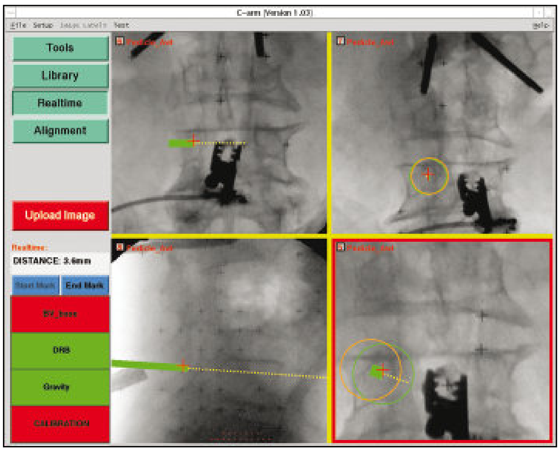
Since the introduction of early CAOS systems, new computer assisted surgery tools and instruments are continuously introduced into the orthopaedic and traumatological surgery rooms throughout the world. Meanwhile these systems have been applied to a considerably large number of interventions, and they are about to become state-of-the-art for certain procedures. Over the years, different concepts and techniques have been developed, realised, and evaluated.

Distance from Entry: 5 mm

Figure 1. Example of CT-based navigational feedback
This screenshot shows a CT based navigation during pedicle screw placement where the optimal location for the screw in L2 has been planned pre-operatively (red line) and the current position and orientation of the instrument used to prepare the screw canal is overlaid as a green line, facilitating precise alignment of the instrument with the plan.

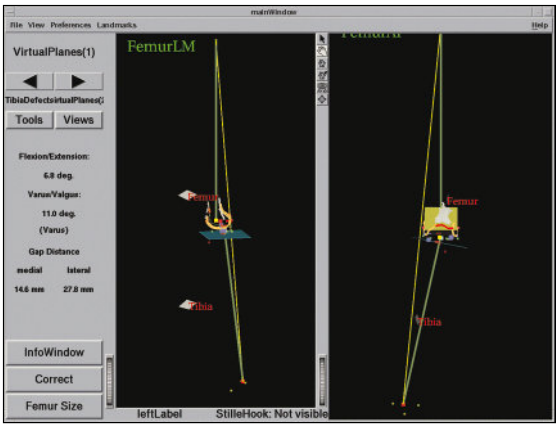
Some of them proved to be successful while others appeared to be dead-end roads and have consequently been abandoned in the meantime.

It is the aim of this article to present the underlying concepts and technologies of these devices and describe different approaches for the various aspects of the methods. Examples of pre-operative or intra-operative imaging modalities, of trackers for navigation systems, of different surgical robots, and of methods for registration as well as referencing are discussed. CAOS modules that have been realized for different surgical procedures will be presented and critically reviewed. Potential pitfalls that may occur with the use of this technology will be discussed.



Realtime:
DISTANCE: 3.6mm

Figure 2. Example of Fluoroscopy based navigation
This screenshot shows the fluoroscopy based navigation during pedicle screw placement. Four different fluoroscopic images are displayed simultaneously with the current orientation and location of a surgical instrument overlaid as coloured graphics.

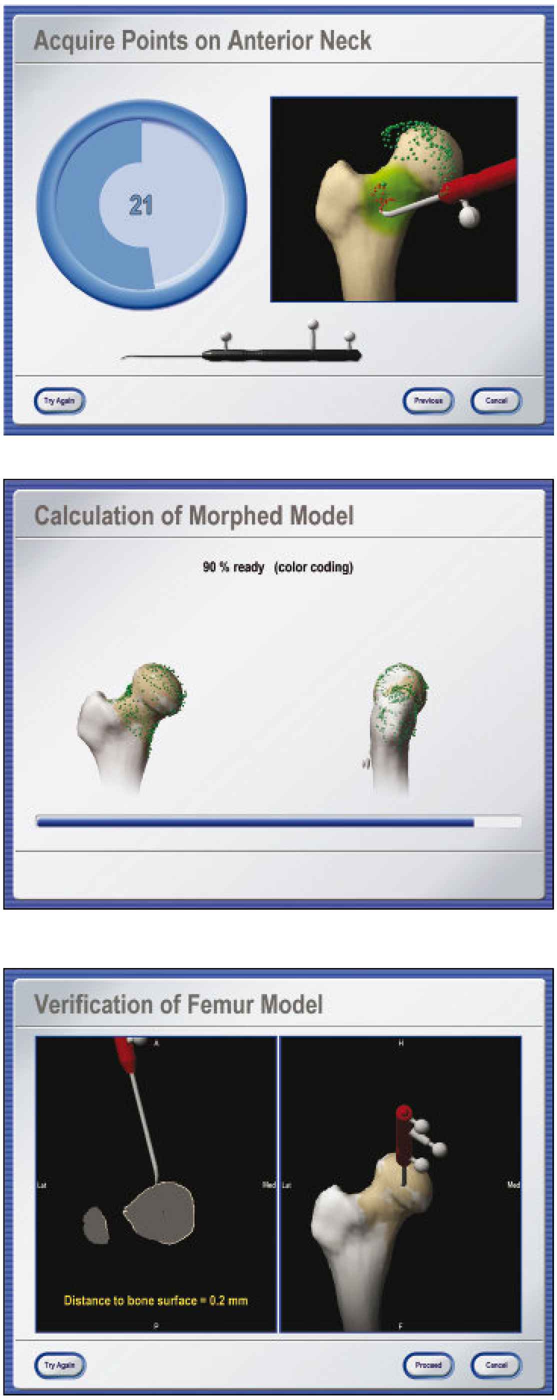


Flexion/Extension:
6.8 deg.
Varus/Valgus:
11.0 deg.
(Varus)
Gap Distance
medial 14.6 mm
lateral 27.8 mm
StilleHook: Not visible

Figure 3. Navigation using Surgeon Defined Anatomy approach
This virtual model of a patient's knee is generated intra-operatively by digitising the relevant structure. Although a very abstract representation, it provides sufficient information to enable navigated placement of a total knee endoprosthesis.

General Concept

Both traumatology and orthopaedic surgery aim at the treatment of bony structures and/or interconnecting soft tissues that are usually located deep inside the human body. Surgical steps such as the placement of an implant component, the reduction of a fracture, or the cutting or drilling of bone should ideally be carried out as precisely as possible. Not only will optimal precision improve the post-operative biomechanical performance of the treatment (6), but it will also guarantee that the probability of intra- and post-operative complications is minimised. A large number of mechanical guides have been developed for various applications in orthopaedics and traumatology. While many of them surely help improving surgical precision, their general benefit has been questioned (see for example (7)). Surgical skills and expertise are definitely the premier methods to achieve a positive operative outcome. However, limited visibility makes it



90 % ready (color coding)

Distance to bone surface = 0.2 mm

Figure 4. Bone morphing
Screenshots of different stages of an intra-operative bone morphing process. (A) Point acquisition; (B) calculation of morphed model; and (C) verification of final result (Courtesy of BrainLAB AG, Munich, Germany)

often difficult to realise the intended procedure as accurately as desired. Large surgical exposures are certainly inappropriate ways to improve visibility, due to the associated tissue damage. Moreover, challenging new techniques of minimally invasive treatment make it more and more important to gain feedback about the action that takes place subcutaneously. Just as laparoscopy and arthroscopy have introduced video transmission to present recorded images of the situs on a video monitor, a CAOS module mimics surgical action in real-time using a virtual scene of the situs presented on a computer monitor (8). This technique was initially developed for frameless intracranial interventions, and after further refinement can now cover various procedures in orthopaedics and traumatology. Another method to potentially improve the outcome of bone surgery is the employment of surgical robots. Being successful in industrial production for many years, their precision and their resistance against tremor and fatigue has been advocated for different applications in traumatology and orthopaedics.

Although CAOS modules use numerous technical methods to realize individual aspects of a procedure, their basic conceptual design is very similar. They all involve three major components: a therapeutic object (the target of the treatment), a virtual object (its virtual representation in the planning and navigation computer), and a so-called navigator that links both objects. For reasons of simplicity, the term “CAOS system” will be used within this article to refer to both navigation systems and robotic devices.

The central element of each CAOS system is the so-called navigator. It establishes a global, three-dimensional coordinate system and thus enables the transmission of positional information between the virtual object (VO) and the therapeutic object (TO). For robotic devices, the robot itself plays the role of the navigator while for surgical navigation a position tracking device is used. The VO and the TO are mathematically linked to the navigator by registration and referencing. The virtual object represents an image of those parts of the anatomy that are operated on with the help of the CAOS system. Examples for each of these elements will be presented and discussed in the following sections.

Virtual Object

The purpose of the VO in each CAOS system is to provide a sufficiently realistic representation of the bony structures involved in a surgical intervention. The image data are visualised on a computer monitor and provide the framework in which computer assisted procedures can be planned. In addition they serve as the intra-operative "background" into which the measured position of a surgical instrument is projected as exemplified in Figure 1.

VOs may be acquired at two points in time: either pre-operatively or intra-operatively. About one and half decades ago, first CAOS systems were introduced that were based on pre-operatively acquired computed tomography (CT) scans. The advantage of this modality is that it provides excellent bone-soft tissue contrast. Moreover, the acquired images are geometrically undistorted and thus no sophisticated calibration needs to be applied. These advantages make CTs superior to magnetic resonance imaging (MRI) as pre-operative VOs, although the latter method has clear advantages regarding radiation exposure to the patient. Some efforts have been made to overcome the MRI related difficulties (9); however, up to now CT remains the method of choice of pre-operative imaging for CAOS applications. Another drawback of pre-operative VOs led to the introduction of intra-operative imaging modalities; the bony morphology may have changed between the time of image acquisition and the actual surgical procedure. As a consequence, the VO may not necessarily correspond to the TO any more, leading to unpredictable inaccuracies during navigation or robotic procedures. This effect can be particularly adverse for traumatology in the presence of unstable fractures. To overcome this problem in the field of surgical navigation the use of intra-operative CT scanning has been proposed (10), but the infrastructural changes that are required for the realisation of this approach are tremendous, often requiring considerable reconstruction of a hospital's facilities. An alternative is the usage of established intra-operative imaging modalities. Several research groups have developed navigation systems based on fluoroscopic images (11,12). The image intensifier is a well-established device during orthopaedic and trauma procedures and could therefore be integrated into CAOS systems easier than intra-operative CT machines. However, the images generated with a fluoroscope are usually distorted, which is caused by a number of factors. To use these images as VOs therefore requires the calibration of the fluoroscope involving the attachment of marker grids to the image intensifier and the tracking of its position and orientation with the navigator during image acquisition (11,12). The resulting real-time visual feedback provided by the navigation system (Figure 2) is similar to the use of the fluoroscope in constant mode. This technique is therefore also known as "virtual fluoroscopy" (13). Although only two-dimensional projections are available and the images usually lack contrast when compared to CT scans, the advantages of fluoroscopy based navigation preponderate for a number of clinical applications.

More recently, a new imaging device was introduced (14) that enables the intra-operative generation of three-dimensional, fluoroscopic image data. It consists of a motorised, iso-centric C-arm that acquires series of 50–100 two-dimensional projections, and reconstructs from them 13x13x13 cm3 volumetric datasets which are comparable to CT scans. Being initially advocated primarily for surgery at the extremities, this "fluoro-CT" has been adopted for usage with a navigation system and has been applied to several anatomical areas already (15). As a major advantage, the device combines the availability of three-dimensional imaging with the intra-operative data acquisition. "Fluoro-CT" technology is under continuous development involving smaller C-arms, faster acquisition speeds, and also flat panel technology.

A last category of navigation systems functions without any radiological images as VOs. Instead, the tracking capabilities of the system are used to acquire a graphical representation of the patient's anatomy by intra-operative digitisation. Using any tracked instrument, the spatial location of anatomical landmarks can be recorded. Combining the obtained points into lines and surfaces will step-by-step generate an abstract model of the geometry. Because this model is generated by the operator, the procedure is known as "surgeon-defined anatomy" (SDA). The technique is particularly useful when soft tissue structures such as ligaments or cartilage boundaries are to be considered that are difficult to identify on CTs or fluoroscopic images. Moreover, with SDA based systems some landmarks can be acquired even without direct access to the anatomy. For instance, the centre of the femoral head, which is an important landmark during total hip and knee replacement, can be reconstructed from a recorded passive rotation of the leg about the acetabulum. It should be noted that the generated images are often rather abstract and not easy to interpret as exemplified in Figure 3. Sati and co-workers suggested the superposition of a pre-operative X-ray to facilitate orientation (16), but the precise matching of the two image spaces turned out to be difficult. An alternative concept is provided by the so-called “bone morphing” (17,18). This technology uses a database of generic, three-dimensional, statistical computer models of bones and a set of patient-specific points that are acquired with the SDA technique. Analysing the recorded data lets the system select that bone model from the data pool that best matches the patient’s morphology. A special morphing algorithm would then deform the selected model three-dimensionally until it fits the acquired points as good as possible. As the result, a realistic virtual model of the operated structure can be presented and used as a VO without any conventional image acquisition (Figure 4).

Registration

Position data that is used intra-operatively to display the current tool location (navigation system) or to perform automated actions according to a pre-operative plan (robot) are expressed in the local coordinate system of the VO. In general, this coordinate system differs from the one in which the navigator operates intra-operatively. In order to bridge this gap, the mathematical relationships between both coordinate spaces needs to be determined. When pre-operative images are used as VOs, this step is performed interactively by the surgeon during the registration, also known as matching. A wide variety of different approaches have been developed and realised following numerous methodologies (19).

Early CAOS systems implemented a feature based registration (20). The technically simplest method of this category is the so-called paired-points registration. Pairs of distinct points are defined pre-operatively in the VO and intra-operatively in the TO. The former set of points is usually identified using the computer mouse and marking the desired location within the image data. For the intra-operative acquisition, a probe is used. In the case of a navigation system, it is tracked by the navigator and for robotic surgery it is mounted onto the robot’s actuator, which the surgeon then passively guides to the location to be recorded (21). Once both point sets are available, the transformation that links the underlying coordinate systems can be derived. It is obvious that this procedure is highly interactive during both the pre-operative definition of registration points and the intra-operative acquisition of their counterparts. Consequently, this step is error-prone, in particular because a good registration result and thus an accurate performance of the CAOS system strongly depend on the optimised selection of these points and the exact identification of the associated pairs. To improve the accuracy of this step, alternative and complementing techniques have been proposed. Probably most obvious is the implantation of artificial objects to create easily and exactly identifiable spots for paired-points registration. Percutaneous pins (21), markers (22), screws (23), or complex marker carriers (24) have been suggested. However, these methods require the artificial markers to be represented in the pre-operative image as well, thus necessitating their implantation prior to CT-scanning with an additional intervention. Although this is usually done under local anaesthesia, the extra operation causes further costs, not to mention the associated discomfort for the patient (25) and the risk of infections. Consequently, none of these methods have gained wide clinical acceptance.

Other methods to calculate the registration transformation without the need for extensive pre-operative preparation utilise intra-operative imaging. As described above, a calibrated fluoroscope may be utilised to acquire VOs intra-operatively. Since the fluoroscope is tracked by the navigator during image acquisition and if the relation between the fluoroscope’s position in space and the resulting image is known, the 2-D projective representations can be matched with a 3-D CT dataset yielding the registration of the pre-operative scan (Figure 5). From a technical standpoint, such a procedure is non-trivial and is still an active research field. Intensive-based as well as feature-based approaches have been proposed before (19).

Another alternative is the employment of intra-operative ultra-sonography. If an ultrasound probe is tracked by a navigator and its measurements are calibrated, it may serve as a space digitiser with which position data of the anatomy may be acquired. It thus can replace any other tracked instrument to digitise landmarks for paired-points or surface registration. Two different tracked mode ultrasound probes are available. A-(amplitude-) mode ultrasound probes yield the perpendicular depth along the acoustic axis of the device. Placed cutaneously they can measure the distance to tissue borders, and the resulting point coordinates can be processed by any registration algorithm. Although the applicability of this technique has been demonstrated (26,27), it is not widely used. The nature of A-mode ultrasound requires the probe to be oriented perpendicularly to the bone surfaces

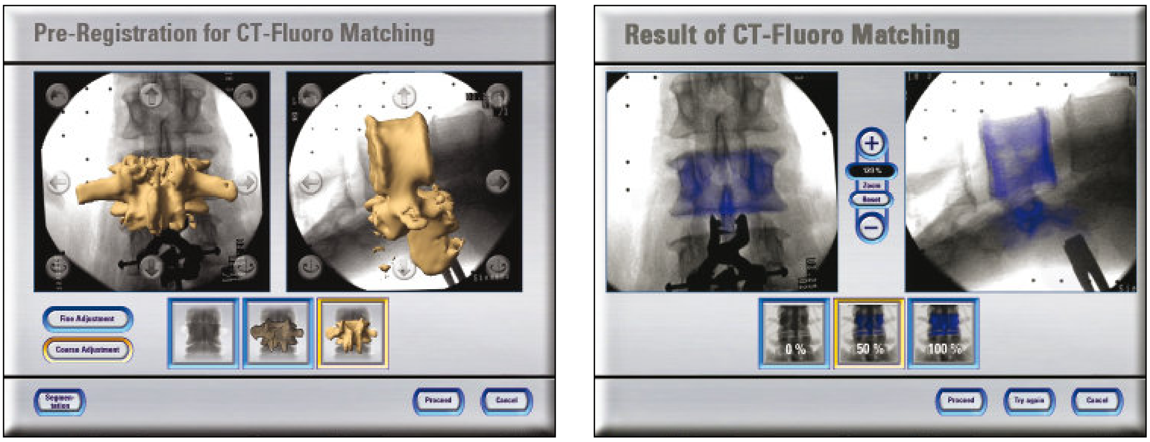


Figure 5. CT-Fluoro Matching
Screenshots of different stages of a CT-Fluoro matching process. (A) Pre-registration for CT-Fluoro matching; and (B) results of CT-Fluoro matching (Courtesy of BrainLAB AG, Munich, Germany)

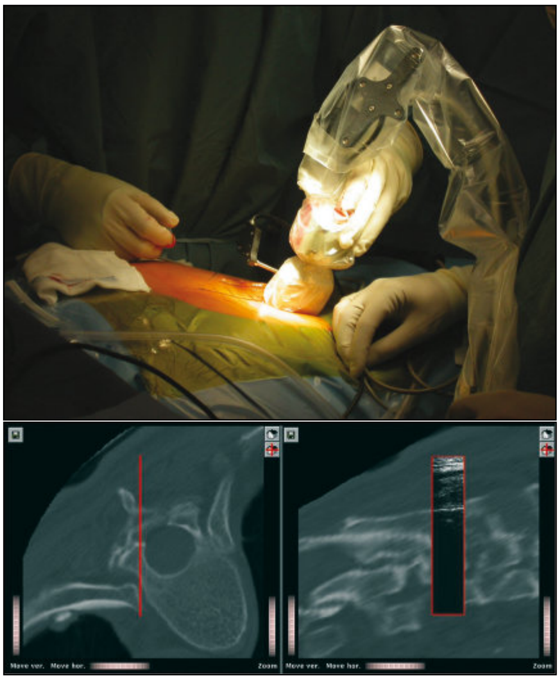


Figure 6 – CT-US Matching
An intra-operative setup for B-mode ultrasound based registration. (A) Intra-operative setup; (B) the final registration results. After registration, ultrasound image information is superimposed onto associated multi-planar reconstructions from the CT data set.

that it aims at. Moreover, the velocity of sound varies depending on the properties of the traversed tissues thus leading to unpredictable inaccuracies when used to digitise deeply located structures. As a consequence, the successful application of this technique remains limited to a narrow field of application (28). In contrast to an A-mode probe, a B-(brightness-) mode ultrasound probe scans a fan-shaped area. It is therefore able to detect also surfaces that are examined from an oblique direction (Figure 6). In order to extract the relevant information for the registration of pre-operative CT scans, the resulting, usually noisy images need to be processed either manually (29) or automatically (30). As for the intra-operative processing of fluoroscopic images, the use of B-mode ultrasound for registration is not reliable in every case and consequently remains subject of CAOS research.

If any intra-operative method is used to generate the VO, registration is an inherent process (19). As stated above, the imaging device is tracked during data acquisition. As a result, the position of the acquired image is known with respect to the TO. This relation corresponds to the interactive registration in the case of pre-operative images serving as VOs. Therefore, registration is not an issue when using intra-operative CT, 2-D or 3-D fluoroscopy, or the SDA concept.

Navigator

Registration closes the gap between VO and TO. The navigator enables this connection by providing a global coordinate space. In addition, it links the surgical

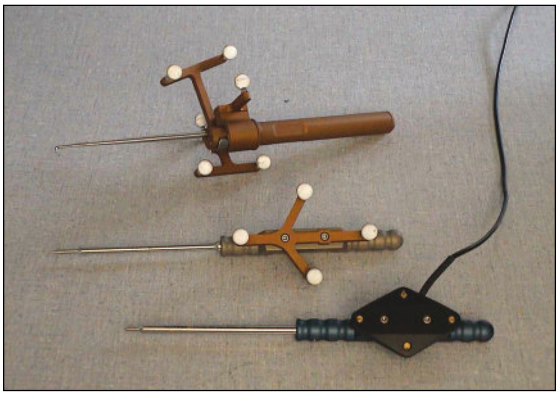
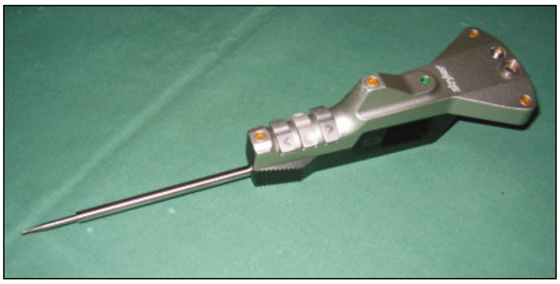



Figure 7 – Optically tracked surgical instruments
a) Reflective spheres may be used for the passive tracking of instruments. These markers reflect infrared light that is emitted by the camera system. In contrast, most of the instruments that are tracked using actively light emitting diodes are controlled and powered via cables that connect the instruments to the tracker.
b) When active tracking of instruments shall be performed without cables, batteries and additional electronics need to be mounted to the instruments.

Figure 8 – Dynamic Reference Base
A dynamic reference base allows a navigation system to track the anatomical structure that the surgeon is operating on. In the case of spinal surgery this DRB is usually attached to the spinous process with the help of a clamping mechanism. It is essential that it remains rigidly affixed during the entire usage of the navigation system on that vertebra.

instruments with which a procedure is carried out, to the TO that they act upon. From a theoretical standpoint, it is the only element in which surgical navigation systems and surgical robotic systems differ.

Robots: For this type of CAOS technology, the robot itself is the navigator. It is registered to the VO which enables it to realise the plan that was defined by the surgeon in the pre-operative image data set. Its actuators carry out specific tasks as part of the therapeutic treatment. Active robots act directly on the patient. They perform a specific task autonomously without additional support by the surgeon. Two robotic systems for total joint replacement have been introduced (4,5), but their clinical benefit has been strongly questioned lately (31). Moreover, they require considerable investments while serving a rather limited portfolio of interventions. As a result, the future of these devices is highly uncertain. For traumatology applications, the use of robots has only been explored in the laboratory setting (32). This may be a tribute to the nature of fracture treatment which is usually a process that needs to be individualised for each case and does seldom include many standardizable steps that a robot could repetitively carry out. Nevertheless, a robotic system for the reduction of long bone fractures has been recently proposed (33). It can be described as motorised Ilizarov type of external fixators with which a planned motion path of a fragment can be reduced automatically. However, the device has a potentially larger field of application in corrective surgery, e.g., during callus distraction. Thanks to its computer controlled interface, the usually difficult motion control of the parallel platforms is facilitated, and continuous micro-motions can be realised over a long period of time.

In contrast to active robotic devices, semi-active robots do not carry out a part of the intervention autonomously, but rather guide or assist the surgeon in positioning the surgical tools. At present there are two representatives of this class that are commercially available, both for bone resection during total knee replacement. The Acrobot system (34) is based on a custom robot. It differs in the purpose that it serves intraoperatively. It holds a high-speed mill that the surgeon is allowed to move freely in order to resect bone as long as this motion stays within a pre-operatively defined safety volume. When the milling action is about to leave this volume causing more tissue to be resected than planned, the robot would actively intercept to block the unwanted movements. This approach enables the surgeon to carry out the actual resection process manually while being assured that the planned cuts are realised precisely. Other semi-active robots can be seen as intelligent gauges that place, e.g., cutting jigs or drilling guides automatically (35,36).

Trackers: The navigator of a surgical navigation system is a position tracking device. It determines remotely the position and orientation of objects and provides these data as three-dimensional coordinates. From a physical point of view, a number of methods exist to remotely sense the location of objects, and basically all of them have been implemented in trackers that in turn were used as parts of navigation systems. Most of today's products rely upon optical tracking of objects using OR compatible infrared light that is either actively emitted from the observed objects or passively reflected by them. In any case, a camera system registers these signals and reconstructs position data. To track surgical instruments with this technology requires the tools to be adapted with probes holding either light emitting diodes (LED, active) or light reflecting spheres or plates (passive, see Figure 7-A). Depending on the used tracker model, the active LEDs are powered and controlled either by a cable or remotely, which requires a battery to be housed by the probe as well (Figure 7-B). Tracking by means of video images has been suggested (37) as an inexpensive and simple alternative to a passive optical tracker, but so far the accuracy of this approach cannot compete with what infrared-light based systems can achieve.

Optical tracking of surgical instruments requires a direct line of sight between the tracker and the observed objects. This can be a critical issue in the OR setting. The use of electromagnetic tracking systems has been proposed to overcome this problem. This technology involves a homogeneous magnetic field generated by an emitter coil. Receiver coils are then attached to each of the instruments allowing to measure their position and orientation within the magnetic field. This technique senses positions even if objects such as the surgeon's hand are in between the emitter coil and the tracked instrument. However, the homogeneity of the magnetic field can be easily disturbed by the presence of certain metallic objects causing measurement artefacts that may decrease the achievable accuracy considerably (38). Therefore, magnetic tracking has been employed only in very few commercial navigation systems and with limited success. Clinical results have been reported in (3). Probably one of the most obvious ways to track an instrument's position is by means of a direct mechanical link. Multi-link arms have been known for many years to be reliable and precise measurement devices. It is obvious though that the physical link between the arm and a usually small surgical instrument is not generally suitable. As a result, the field of application of mechanical trackers as parts of surgical navigation systems is narrow (39).

Referencing

Relative motions between the TO and the navigator need to be detected and compensated to secure surgical precision. To do so, the operated anatomy is linked to the navigator. For robotic surgery this connection is established as a physical linkage. Large active robots, such as the early machines used for total joint replacement, come with a bone clamp that tightly grips the treated structure or involve an additional multi-link arm, while smaller active and semi-active devices are mounted directly onto the bone. An equivalent strategy is required when a mechanical arm is used as the navigator. For all other tracker types, bone motion is determined by the attachment of a so-called dynamic reference base (DRB) to the TO (40). It houses infrared LEDs, reflecting markers, acoustic sensors or electromagnetic coils, depending on the employed tracking technology. Figure 8 shows the example of a DRB for an active optical tracking system that is attached to the spinous process of a lumbar vertebra. Since the DRB is used as an indicator to inform the tracker precisely about movements of the operated bone, a stable fixation throughout the entire duration of the procedure is essential.

Clinical fields of application

Since the mid-nineties when first CAOS systems were successfully utilised for the insertion of pedicle screws in the lumbar spine and total hip replacement procedures, a large number of modules covering a wide range of traumatological and orthopaedic operations have been developed, validated in the laboratory and in clinical trials. Some of them needed to be abandoned, because the anticipated benefit failed to be achieved or the technology proved to be unreliable or too complex to be used intra-operatively. Discussing all these approaches and methods would go beyond the focus of this article. Nevertheless, a review of the most important systems and the most original technological approaches shall be presented here.

While there was clearly one pioneering example of robot assisted orthopaedic surgery – ROBODOC (4), several research groups realized first spinal navigation systems independently from each other, yet almost in parallel (3,40–44). These systems used pre-operative CT scans as the VO, relied upon paired-points and surface matching techniques for registration, and used different optical or electromagnetic trackers. Their clinical success (45–47) made them initiate a world-wide search for further applications and boosted the development of new CAOS systems and modules. While some groups tried to use the existing pedicle screw placement systems for other clinical applications, others aimed to apply the underlying technical principle to new clinical challenges by developing highly specialised navigation systems (48,49). With the advent of alternative imaging methods for the generation of VOs, the indication for the use of one or the other method was evaluated more critically. For instance, it became evident that lumbar pedicle screw insertion in the standard degenerative case could be carried out with fluoroscopy-based navigation sufficiently accurately; thus avoiding the need for a pre-operative CT.

A similar development took place for total knee replacement. Initially, this procedure was supported by active (50) and semi-active (34) robots, as well as navigation systems using pre-operative CTs (51) but with a few exceptions the SDA approach is today's method of choice (52).

Fluoroscopy-based navigation still seems to have a large potential to explore new fields of application. The technology has been mainly used in spinal surgery (53). Efforts to apply it to total hip replacement (54) and the treatment of long bone fractures (55) have been commercially less successful. The intra-operative three-dimensional fluoroscopy has been explored intensively (15,56). It is expected that with the advent of the flat panel technology, the use of fluoro-CT as a virtual object generator will significantly grow.

Potential Pitfalls of CAOS

CAOS systems and modules have become widely available for the treatment of a growing number of interventions in orthopaedics and traumatology over the past 10 years. It is now undoubted that these devices can reduce the variability in implant placement (57), increase the accuracy with which a certain operation can be carried out (58), and thus may ultimately improve the overall outcome of a surgical treatment. The simplicity of the navigational feedback was observed (59), and manufacturers of these devices point out the ease of handling. However, the successful application of a surgical navigation system requires the ability to control a still complex technology. Deep understanding of the underlying concepts, their strengths as well as their weaknesses is of great advantage when applying CAOS technology. Some 15 years after the first experimental application in spine surgery (3,40–42), CAOS has clearly emerged from the laboratory and there is a lot of room for improving the technology. However, it should be noted that navigational support of surgical interventions in particular in the hands of inexperienced users is not a fool-proof technique and may lead to potential pitfalls.

The majority of navigation systems involve the remote tracking of surgical instruments and anatomical structures. The most commonly used technique is that of optical tracking based on infra-red light emitting diodes (LEDs) or infra-red light reflecting markers. The camera system that has to observe the resulting signals obviously needs a direct line-of-sight to the objects of interest. Determining the right camera position in the operating room depends on a number of factors, such as the available space, established positions of the surgical staff around the operating table, preferences of the surgeon (e.g., positioning of the patient), cable lengths between the components of the CAOS system, etc. Moreover, tracking cameras have an optimal operating distance at which they perform best. Other light sources such as operating lights or the light of an operating microscope may interfere with the tracking technology causing serious accuracy deterioration. Warm-up of some cameras for a certain time period (up to 20 minutes) before the navigational support is recommended.

However, not only the placement of the tracking camera must be carefully considered. A navigation system usually introduces a considerable amount of new equipments into the OR, and its optimal positioning may facilitate the successful application of the technology. The monitor providing feedback to the surgeon needs to be visible to him/her without any problems, which may require a slight change of the position of the assistant. If actively tracked instruments are used, the scrub nurse will require special training to deal with the instruments' cables without ending up with "cable spaghetti".

In general, for each new procedure, placement of the equipment within the OR as well as on the instrument table must be carefully evaluated and defined. Manufacturers provide recommendations only for the most common surgical applications and even these may need individualization for the single clinic. If a system is used by more than one OR team or if it is employed during different types of operations, it may be wise to mark the optimal placement of each component on the floor of the OR to ensure correct set-up without any time loss.

During the usage of a CAOS system, the surgeon should be familiar with the underlying concepts and the complications that may result from incorrect handling. A DRB is used to track the operated bone structures. The DRB is the only way by which the tracking camera can "see" the patient's anatomy. It is therefore absolutely essential that this device is fixated to the bone in a very stable manner and remains in its initial position for the entire time of the navigated procedure. If there are doubts about the consistency of the DRB position at any time, it must be verified immediately. The necessary methods to do so are available in each navigation system. A bad correspondence between the tracked DRB position and the real location of the operated bony structures can also be a result of an instable anatomical situation. A DRB must be used to reference only one bone or bony fragment. If the treatment of several bone objects is required (e.g., during fracture reduction or spinal instrumentation), the objects need to be treated simultaneously using multiple DRBs or consecutively with the DRB moved between each step.

The discrepancy between what is visible to the camera and what is of interest for the surgeon applies to the navigated instruments, too. The concept of remote instrument tracking relies upon the rigid body principle, i.e., each tracked instrument is assumed to be non-deformable. Especially for slender tools, this may be difficult to achieve. Thin drill bits or Kirschner wires bend easily. If they are operated with an optoelectronically tracked drill or T-handle, the resulting navigational feedback will be inaccurate because the CAOS system assumes the entire instrument to be rigid. It the surgeon is aware of this effect, it can be respected by relying upon the navigation screen only in states when the tracked instrument is undeformed. Nevertheless, the use of a navigated drill sleeve is surely safer and more accurate.

A more subtle effect can sometimes be observed for passively tracked instruments using reflective marker spheres. With increasing cycles of re-sterilization or when the spheres are partially obscured or covered, e.g., with blood, tracking accuracy may drop. Navigation manufacturers have reacted recently by introducing new types of markers so that this sort of problems may be of less importance in the future.

A totally different aspect of the application of computer assisted surgery is that of the overall costs. Surgical navigation is a rather new technique in the field of orthopaedics and traumatology. Consequently, there are no long-term results available that can prove the benefit of this technique. However, a number of initial studies suggest increased surgical accuracy and thus may ultimately lead to lower complication rates (46). This may prove worth the investments that are required for purchasing and maintaining a navigation device and the observed additional per-case costs. Nevertheless, it should be carefully checked which type of surgery can be best served with which type of navigational approach. It should be considered that for certain interventions the financial and logistical expenses and the possible CAOS-related difficulties are not worth the effort, and that a conventional treatment may be the better choice.

Conclusions

More than 15 years have passed since the first robot and navigation systems for CAOS were introduced. Today this technology has emerged from the laboratory and is being routinely used in the operating theatre and might be about to become state-of-the-art for certain orthopaedic procedures.

Still we are at the beginning of a rapid process of evolution. New techniques will constantly be invented or derived from existing methods. Hybrid navigation systems are under development, which will allow the surgeon to use any combination of the above-described concepts to establish virtual object information. New generations of mobile imaging systems, inherently registered will soon be available. However research focus should particularly be on alternative tracking technologies, which remove drawbacks of the currently available optical tracking devices. This in turn will stimulate the development of less or even non-invasive registration methods and referencing tools. Force sensing devices and real-time computational models may allow establishing a new generation of CAOS systems by going beyond pure kinematic control of the surgical actions. For key-hole procedures there is distinct need for smart end-effectors to complement the surgeon in his/her ability to perform a surgical action.

All these new techniques and devices need to be carefully evaluated first in the laboratory setting and then clinically. However, it may be hypothesised that the ultimate acceptance of robotic or navigated bone surgery will be contributed to the proof of better long-term results. Consequently, more prospective (and retrospective) studies comparing the outcome of CAOS vs. non-CAOS procedures with long follow-up times will have to be conducted.

Still it is essential to understand that the navigational support of surgical interventions will never be a fool-proof technique. The surgeon who operates with a CAOS system must understand the concepts and limitations of the employed methods. Otherwise, the large beneficial potential that modern CAOS systems make available cannot be exploited effectively for the benefit of the patient.

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