Current state of computer-assisted trauma surgery

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Abstract Computer assisted surgery (CAS) was first used in neurosurgery. Currently, CAS has gained popularity in several surgical disciplines including urology and abdominal surgery. In trauma and orthopaedic surgery, computer assisted systems are used for fracture reduction, planning and positioning of implants as well as the accurate implantation of hip and knee prostheses. The patient's anatomy is virtualized and the surgical instruments integrated into the digitized image background, thus allowing the surgeon to navigate the surgical instruments and the bone in an improved, virtual visual environment. CAS improves overall accuracy, reducing intraoperative radiation exposure and minimizing unnecessary surgical dissection combined with increased patient and surgeon safety. However, limitations include prolonged surgical time, technical errors and cost implications. This article will outline the current state of computer assisted trauma surgery including its implications and specific challenges in orthopaedic trauma surgery.

Keywords Computer assisted surgery · Navigation · Trauma · SI-screw · Femur · Femoral malrotation

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Introduction

Computer assisted surgery (CAS) was first introduced in neurosurgery to reduce intraoperative iatrogenic complications; this was achieved with preoperative CT images and adjustment of intraoperative reality using highly specialized software. De rigueur in the 1990s introduced CAS in trauma and orthopedic surgery. A rapid advancement and improvement in navigation and imaging technology including newer soft and hard applications provided increased accuracy, reduced intraoperative radiation exposure, and minimized invasiveness. Over the years, several manufacturers have developed various navigation modules using imaging modalities to meet the surgeon's individual requirements. Intraoperative menu-driven software and user-friendly hardware have improved considerably, however, system reliability, accuracy, and plausibility remain problematic [1–4].

CAS matches pre- or intraoperatively generated image data with the patient's anatomy. Via infrared signals, data are sent and detected by a camera. The computer then calculates the position of the single components in relation to each other and visualizes their position on the monitor in image data. The surgeon monitors the position of the instruments in relation to the patient's anatomy in real time and plans the procedure accordingly, such as inserting a screw on a virtual base [1, 3, 5].

Imaging modalities for navigation

Preoperatively acquired computed tomography

After applying reference fixation on the patient, computed tomography (CT)-data are matched with the patient's anatomy. The surgeon identifies predefined landmarks in situ, using a pointing device, which are matched with the landmarks of the CT dataset. The advantage of this image base is

the high resolution quality of the three-dimensional (3-D) dataset. However, disadvantages include time-consuming registration and unnoticed errors that may substantially impair precision [1, 3].

Preoperatively acquired magnetic resonance imaging

This modality works similar to the previously described CT scan [6]. Both intraoperative acquired CT or magnetic resonance imaging (MRI) are predominantly used in neurosurgical and spinal surgery [6].

Intraoperative two-dimensional (2-D) fluoroscopy was introduced in 1999 and is the most commonly used image base modality in trauma navigation. Generally, 2-D or 3-D image data from a mobile C-arm are transferred to the navigation system. Meanwhile, new software applications have been developed, which allow the fusion of a preoperatively acquired dataset (CT or MRI) with an intraoperatively acquired dataset or other preoperative data sets [7, 8].

Intraoperative 3-D fluoroscopy

These 3-D C-arms usually consists of standard mobile C-arm systems, coupled with a motor, hardware, and software components for 3-D imaging. The 3-D imaging is then performed by calculating multiplanar reconstructions out of 50 to 100 C-arm images that are registered during 1 automated or semiautomated rotating scanning procedure and high resolution 3-D data is subsequently calculated. From this data set, axial scans are first generated following reconstruction into coronal and sagittal slice orientations. Based on the possible dynamic visualization and active scrolling of the images, the surgeon can use the generated multiplanar reconstructions to aid in performing accurate fracture reductions and determine the appropriate implant and accurate application. During the scanning procedure, the automated scan should not be disturbed by any collision of the rotating C-arm, as this will cause an immediate scan stop and failure. After scanning, the data set may also be transferred to any navigation system. The navigation system allows for visualization of specific navigated surgical tools in all 3 cardinal or non-cardinal planes [7, 8].

Image-free modules

These are the basis of navigation in hip and knee arthroplasty as well as high tibial osteotomies and in arthroscopic-supported retrograde drilling of osteochondral lesions. Using pivoting mechanisms to determine the center of the hip joint and algorithms to define the ankle and knee center of rotation, a navigated measurement of the mechanical limb axis is possible. Additional application of predetermined landmarks allows a combined image free

visualization of the hip or knee joint, including the mechanical limb axis in relation to the desired implant position [9, 10].

Challenges in trauma surgery

In the orthopaedic field, a prospective single-center study showed the improved clinical outcome in patients who had undergone computerized navigated total knee replacement. After 5 years, patients with navigated total knee arthroplasties resulted in a better mean Knee Society score ($P=0.008$) compared with patients who underwent the procedure with the conventional technique. No significant difference in the frequency of malalignment was seen between the 2 groups [11]. Recently Taller, et al attempted to study the clinical outcome of patients who underwent percutaneous screw fixation of pelvic ring and the acetabular fractures, however, as a consequence of the heterogenous patient-population and the various fracture patterns it was impossible to reach statistical significance [12].

The favorable effect of an anatomically reconstructed articular surface after an intra-articular fracture is well documented; biomechanical stresses caused by incongruence and malalignment lead to abnormal unphysiological force vectors with a resultant adverse functional outcome [13].

Pelvis and hip surgery

Due to the complexity of the bony anatomy and close proximity of neurovascular structures, the operative management of traumatic unstable pelvic ring injuries and acetabular fractures can prove considerably challenging even to the experienced trauma surgeon. Iliosacral screw fixation is considered the gold standard in stabilizing osseous and ligamentous posterior pelvic ring injuries, however, screw insertion can be technically challenging with relatively narrow safe zones [14]. Percutaneous screw insertion avoids open surgical approaches and potential complications including wound necrosis and infection. Navigation-assisted percutaneous screw fixation allows for accurate screw placement avoiding the risk of implant-related and neurovascular complications associated with conventional placement of iliosacral screws (Figs. 1 and 2) [15, 16].

Zwingmann and Oberst [17•] prospectively collected data of patients with unstable fractures of the posterior pelvic ring, including only type B and C fractures according to the classification of Tile and Pennal. Twenty-four patients (26 screws) were treated with 3-D fluoroscopy based navigated iliosacral screw placement from 2006 to 2008. They compared radiation exposure and screw position in these patients with those of 32 patients (35 screws) who had conventional fluoroscopy before navigation was introduced at their institution. The screw position was determined with postoperative CT scans. An ideal screw position was

Fig. 1 Intraoperative setup of percutaneous iliosacral screw placement during navigated drilling. The patient is positioned supine, the navigation references are fixed on the iliac crest and on the drill. The surgeon supervises the procedure's progress on the navigation monitor

considered to be entirely within the cortical margins of the sacrum and parallel to the respective sacral end plate and the S1 neural foramina. Perforations were graded (grade 0–3) according to an established classification method used for correct pedicle screw placement [18]. The radiation time ($P=0.003$) and dose ($P=0.001$) were decreased in the navigated group (63 ± 15 seconds; range, 36–84 seconds; 822 ± 164 cGy/cm²; range, 542–1145 cGy/cm²) compared with time and dose in the conventional group (141 ± 69 seconds; range, 42–252 seconds; 1843 ± 1052 cGy/cm²; range, 600–3811 cGy/cm²). They observed a greater percentage of

Fig. 2 Accurate screw position after 2-D image based navigated bilateral iliosacral screw placement

correct screw positions ($P=0.02$) in the navigated group with grade 0 in 69 % (grade 1, 15 %; grade 2, 8 %; grade 3, 8 %) compared with correct screw position in the conventional group with grade 0 in 40 % (grade 1, 37 %; grade 2, 11.5 %; grade 3, 11.5 %) [17••].

Zwingmann and Oberst also compared 54 patients (63 screws) with 3-D fluoroscopy based navigated iliosacral screw fixation with 87 patients (131 screws) stabilized using the conventional fluoroscopic technique. A complete intraosseous screw position was found in 42 % of cases using the conventional technique which was significantly lower when compared with 81 % using a 3-D image intensifier in combination with a navigation system ($P<0.001$). Moreover, the revision rate of 1.6 % was significantly lower in the navigated group compared with 19 % in the conventional group ($P<0.0007$) [19••]. The operative expertise of the surgeon however, is the most significant factor in correct screw positioning regardless of navigation or more conventional techniques [20].

In a laboratory study performed using plastic models and cadavers, Behrendt and colleagues [21] evaluated the 2-D and 3-D fluoroscopy based navigation for iliosacral screw fixation. They also compared radiation exposure and screw positioning. Three-dimensional-navigation showed significantly better accuracy results than 2-D-navigation, however, 2-D-navigation showed no significant differences compared with conventional procedures. In contrast to Oberst's workgroup, the dose-area product was considerably lower with the conventional technique than with the 2-D and 3-D-navigated techniques. The dose-area of the 2-D-navigated procedure was double ($P<0.001$) and the 3-D-navigated procedure was 5-fold higher ($P<0.001$) than that of the conventional procedure [21].

Similar results were demonstrated by Gras et al [22]. They investigated the accuracy of screw placement, the applied radiation dose and intervention time of 2-D vs 3-D-navigated percutaneous screw placement for acetabular fractures in a laboratory study with a synthetic bone model. Different osseous corridors including the supraacetabular region, anterior column, posterior column, and infraacetabular corridor were used. The overall procedure time per pelvis was significantly reduced in the 3-D group compared with the 2-D group ($P<0.0001$). No differences were observed for the fixation of the dynamic reference base and the calibration of instruments. The time of image acquisition was similar for both procedures. The times of screw planning ($P<0.0003$) and navigated drill bit placement ($P<0.0001$) per pelvis were significantly reduced with 3-D compared with the 2-D navigation procedure.

Cumulative fluoroscopy time was significantly higher in the 3-D-navigated group with an increased precision in screw positioning. The author mentioned that particularly with very narrow corridors like the infra-acetabular screw

path, the use of 3-D navigation is beneficial with an additional advantage of the 3-D image-based navigation software to visualize the planned screw path before commencing drilling. A virtual movement through the 3-D data cube along the planned screw axis in perpendicular slice images facilitates the secure evaluation of the complete intraosseous path [22].

In 2010, Ochs et al [23•] compared periacetabular screws placed using conventional techniques, 2-D- and 3-D-navigation in a synthetic bone model and alcohol-fixed human cadavers. The study confirmed significant results with prolonged radiation time, increased dose-area products, and high accuracy in periacetabular screw positioning with 3-D-image based navigation vs 2-D-image based navigation (perforation rate 7 % vs 20 %). Furthermore, although prolonged overall intervention time was observed, screw placement itself was navigated significantly faster. Image acquisition required more time using 2-D fluoroscopy compared with 3-D fluoroscopy [23•].

Behrendt, Gras, and Ochs demonstrated increased radiation exposure by 3-D-based navigation applications when compared to other examinations. This could be due to the laboratory based-nature of their research, however, the use of a reliable intraoperative 3-D image intensifier avoids the need of a postoperative CT-scan [21, 22, 23•].

Demographic trends predict an increasing population older than age 65 years [24, 25]. This, combined with a greater number of hip and knee replacements being performed each year, contributes to increasing numbers of periprosthetic femoral fractures about total hip (THA) and total knee arthroplasties (TKA) [26, 27]. Fractures around the acetabular component in total hip arthroplasty are rare and can be particularly difficult to manage especially in patients with multiple comorbidities who cannot tolerate complex revision procedures. In these situations, navigated percutaneous screw placement offers a viable solution for minimally displaced but potentially unstable fractures [28].

Femoral application

Femoral shaft fractures are commonly fixed with intramedullary nails. Femoral malrotation and leg length discrepancies are not uncommon complications and can significantly affect clinical outcomes leading to residual pain and premature arthritis [29••]. Femoral torsion is defined as the angular difference between the femoral neck axis and the transcondylar axis of the knee and is variable from patient to patient. Strecker, et al specified the anatomical values of femoral torsion to be $23.77 \pm 18.27^\circ$ for the right side and $24.46 \pm 16.30^\circ$ for the left. There was no significant difference between the sides ($P=0.37$) [30].

Computer-assisted navigation systems facilitate 2-D images to determine the torsion and length of the contralateral femur and transfer this data to the injured side. Using

two Schanz screws eccentrically placed in safe zones without contacting the intramedullary device, the proximal and distal fracture fragments are tracked (Fig. 3). The planning for the torsional adjustment is done on a touchscreen of the navigation module. Four predetermined landmarks are relevant for matching: center of the femoral head; apex of the greater trochanter; lateral posterior femoral condyle; and medial femoral condyle. Depending on the fracture pattern and the surgeon's preference, antegrade, or retrograde nailing can be performed. The surgeon controls, in real-time, the fracture reduction and nail insertion process on the monitor (Fig. 4). Interlocking can also performed using navigation without re-radiation. The reported mean radiation exposure for interlocking screw fixation is 69 ± 34 seconds [29••, 31].

Gardner et al [31] showed that freehand interlocking led to rotational shifts of up to 7° (mean, 5.88 ; range, 4 – 7°), and navigated insertion led to a change of 2.0° (range, 1 – 3° ; $P<0.05$). In a laboratory setting, antegrade nailing of human cadaveric transverse femoral fractures was performed with freehand and navigated distal interlocking compared. Femoral anteversion was measured before and after interlocking, conventional freehand interlocking led to the drill bit frequently contacting the screw hole in the nail with manual adjustment of the drill causing rotation of the distal fragment around the nail. Mathematically in an average femoral circumference of 90 mm, a linear shift of 4 mm along the arc leads to 16° of rotation. Consecutive drill-nail contact and fracture movement during the intervention was noted. Drill-nail contact and a visible shift of the fracture site occurred in all freehand trials, whereas in the navigation group, contact occurred in only one trial without a fracture shift [31].

The clinical accuracy of femoral nailing navigations tools were studied by Wilharm et al [32]. Forty patients with femoral shaft fractures were treated with navigation

Fig. 3 Intraoperative setup of navigated femoral nailing. The navigation references are fixed in safe zones in the proximal and distal fracture fragment without contacting the intramedullary device

Fig. 4 An intraoperative screenshot of the navigation system. The navigation provided real-time feedback of the reduction process (on top) and the mechanical data (below)

supported antegrade or retrograde nailing and reexamined using CT-based length and torsion measurements. Postoperative CT evaluation revealed a realignment of the anteversion up to a mean deviation of $5.4 \pm 3.58^\circ$ compared with the contralateral side. The CT measurements differed from values set intraoperatively with navigation guidance by $7.3 \pm 5.3^\circ$. Femur lengths differed postoperatively by 4 ± 4 mm, although in some cases surgeons accepted slight shortening to lower the risk of pseudoarthrosis. Wilharm also reported, that freehand interlocking can lead to relevant anteversion deviation of up to 10° [32].

Conventionally treated fractures can lead to clinically significant malrotations of 15° in up to 28 % of cases in unilateral femoral shaft fractures [33]. A higher incidence of significant malrotation in bilateral femoral shaft fractures compared with unilateral femoral shaft fractures have been

reported by Citak et al [34]. Navigation assisted femoral nailing prevents pronounced malrotations and extensive radiation, which often occur routinely in the context of reduction and interlocking control.

A further application of computer assistance in femoral trauma is LISS (Less Invasive Stabilization System, Synthes, Paoli, PA) plate placement. A laboratory study was conducted by Al-Ahaideb et al [35] to compare navigation assisted application to the conventional technique. In the navigated group, no hole re-drilling was required, and there was significant differences in accuracy noted when measuring the maximum distance between the LISS plate and the diaphysis (mean value conventional 3.38 vs navigated 6.44; $P=0.04$), but not when measuring the maximum distance to the condyles (mean value conventional 2.69 vs navigated 2.44; $P=0.60$). A significant reduction in radiation exposure

was noted (mean value conventional 9.8 vs navigated 7.0; $P=0.05$), however, a significant prolonged intervention time (mean value conventional 8.42 minutes vs navigated 16.31 minutes; $P=0.04$) was also recorded [35]. Arthroscopic controlled reduction of femoral condyle depression fractures via a retrograde navigated approach is reported by Gras et al [36] to avoid the approach-related morbidity of an arthrotomy using fluoroscopy-free navigation guidance. After the pre-calibrated pointer was arthroscopically placed on the intraarticular fracture side, a second device was inserted via an additional 1 cm skin incision in the medial supracondylar region of the femur. The fracture was reduced with an indirect retrograde approach and fixed with a bone clamp and biodegradable interference screws [36]. This procedure could be emulated in more common fractures like tibial plateau depression fractures and perhaps used in combination with minimally invasive plate osteosynthesis.

In a case series of 4 patients with proximal tibia fractures it was demonstrated, that it is possible to calculate using a defined software application a 3-D template based on 2-D-image acquisition. The implant was virtually integrated; in this case a LISS plate. The entire reduction and fixation procedure was performed without the need for radiological image updates, no technical errors occurred, and post-operative radiographs showed sufficient reduction and well-placed LISS plates [5].

Limitations

Precise and accurate navigation is a question of image modality and quality. Two-dimensional and 3-D image based navigation are the most commonly used application modes. In 3-D image acquisition, the C-arm rotates 190° on a spherical or elliptical orbit around the isocentrum. A fully radiolucent carbon fiber table is required to generate a 3-D data set without metal artifacts of the operation table. Furthermore, the device diameter requires correct and preoperatively confirmed patient positioning to keep the area of interest in the isocentrum. Complex trauma patients with external fixators, sophisticated operative positioning or obesity can make image acquisition extremely challenging and even unsuccessful. The scan volume is limited to 12 cm³ and image quality localization can be demanding. Newer image intensifiers with enlarged device diameters and 360° rotation are available which generate superior image quality, and intraoperative 3-D reconstructions and flat panel detectors provide increased scan volume [7, 8, 37].

Navigation modules are precise measurement tools, but the theoretical precision of 1 mm or 1 degree can only be achieved if precise handling is achieved. The setup can be demanding: instruments should be accurately tracked, reference trackers accurately placed and base references fixed in position after the first registration, otherwise a mismatch can

occur. CAS can prove particularly difficult in emergency poly-trauma scenarios, when more than one surgical team is present [1, 3].

Education of surgeons and operating room staff is essential within the framework of various interventions. At our institution one surgical minute costs roughly \$65. Cost therefore needs to be taken into consideration when considering CAS, and cost must be weighed against intraoperative precision, new minimally invasive techniques, and reduced radiation exposure. Perhaps in the long term a general economical benefit may be demonstrated by improved clinical outcomes and minimizing early and late secondary complications.

Another disadvantage is often the incompatibility of single manufacturers' components. Some provide high image resolution, others an exact and reliable navigation module with few application possibilities, and others provide more innovative implants. The so called closed or semi-open systems restrict its application to the manufacturer, promote intra-operative workflow difficulties and staff disaffection. Navigation devices cost around \$140,000 to \$220,000, and trauma software and additional tools may cost up to \$60,000 [1]. The decision to invest in navigation should be based on the surgeon's preference and patient requirements and not on industrial or administrative pressures. University hospitals limit their investment opportunities to new technologies from other manufacturers over the years and even with implementation of integrated navigation operation theaters, these systems require regular upgrades and updates. The industry should address these concerns if navigation is to gain more popularity and advance its application in trauma and orthopaedic surgery [38].

Conclusion

Computer-assisted surgery may provide more surgical accuracy and safety for patients, surgeons, and operating room staff. Clinically, radiation time is significantly reduced and previously complex invasive procedures can often be performed using minimally invasive techniques. The high costs should be weighed against the benefits of CAS in preventing complications in terms of revisions associated with screw malpositioning in pelvic and acetabular surgery, malpositioned arthroplasty components leading to residual deformities, and failure of adequate reductions, particularly in intra-articular fractures. Minimally invasive procedures lead to less tissue damage with improved wound healing and consequently reduced secondary infections as well as the added aesthetic benefit to the patient. Prospective randomized controlled trials, which prove the superiority of computer-assisted trauma surgical procedures toward conventional techniques, are lacking. To our knowledge, no study has

demonstrated an improved clinical outcome by navigated trauma surgical procedures.

Because of the anatomic complexity and often limited visualization, especially in pelvic and acetabular trauma, efficient fracture reduction can be difficult. New software modules allow the surgeon 3-D-virtual planning of reduction maneuvers which can reduce iatrogenic cartilage and soft tissue damage as well as provide more accuracy and an overall reduction in operation times. By finite element based computational models, force vectors before, during and after fracture reduction can be calculated. Additionally, ideal implant position and mechanical stability of osteosynthesis can be planned. In the future, navigation tools will allow individual fracture reduction maneuvers, perfect implant alignment, and positioning performed through a minimally invasive navigated technique.

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