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Current concepts and applications of computer navigation in orthopedic trauma surgery

D. Kendoff*, M. Citak, T. Hüfner, S. Chaudhary and C. Krettek

Trauma Department,
30625 Hannover Medical School,
Germany

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Abstract: Navigation has become widely integrated into regular endoprosthetic procedures, but clinical use of navigation systems in orthopaedic trauma has only been implemented in a few indications. Navigation systems enable an accuracy of 1 mm or 1 degree. Navigation can achieve higher precision when it is combined with different imaging modalities, including preoperative computer tomography (CT), intraoperative CT, two-dimensional fluoroscopy, and, recently, intraoperative three-dimensional fluoroscopy. The precision of the navigation system can be influenced by the surgeon as well as by the camera system, type of reference marker, and the registration process. Recent developments in orthopedic trauma navigation allow for bilateral femoral anteversion measurements, noninvasive registration of an uninjured thigh, and intraoperative three-dimensional fluoroscopy-based pedicle screw placement. Although the use of navigation has provided initial positive results in trauma care, prospective clinical studies remain to be performed.

Keywords: computer-assisted orthopaedic surgery, navigation, precision, trauma

1 Introduction

Recent developments in computer-assisted technologies have improved intraoperative visualization and guidance in orthopedic and trauma surgery [1–4]. All applications of these new technologies should aim to improve accuracy, reduce the intraoperative exposure to radiation, and minimize the invasiveness of the operative procedure. Choice of the manufacturer, navigation module, and available imaging modality requires careful evaluation. In addition, the accuracy achieved with the navigation system is an important variable.

* E-mail: kendoff.daniel@mh-hannover.de

Essentially all existing imaging modalities can now be used for navigation. These include following:

- Preoperative computed tomography (CT)
- Intraoperative CT
- Two-dimensional (2D) fluoroscopy
- Intraoperative three-dimensional (3D) fluoroscopy

The choice of modality depends on the installed equipment, the indication, and the specific knowledge of the surgeon. Image-free navigation modules have been mainly established in total joint reconstruction, and they have been introduced for high tibial osteotomies. Here, we discuss the opportunities and limitations of recent imaging modalities in orthopedic trauma indications. This includes an overview of the general precision of the various navigation systems in orthopedic surgery.

2 Imaging Modalities

2.1 Preoperative CT Data

Preoperative CT image data was first used for orthopedic navigation to guide the implantation of pedicle screws [5, 6]. This was because CT was already a standard diagnostic tool for spine fractures, while intraoperative control with conventional fluoroscopy technology was limited and pedicle screws had a high potential for misplacement and associated complications. Furthermore, several studies showed that this technology resulted in showed substantial improvements in the precision of navigation compared to conventional technologies [2–4].

Despite these advances, the major problem in surgery remained the initial registration process of matching the preoperative CT data with the current anatomy. This registration process can frequently prolong the operative procedure, and errors may remain unnoticed, substantially impairing the precision of the procedure. This has been shown in anatomically difficult areas, including the thoracic and cervical spine. Problems are due to the fact that the operating surgeon has limited control during the verification process. Recent navigation modules therefore include intraoperative fluoroscopy to aid in the verification process.

Recently, CT-based navigation has become increasing used for indications with complicated surgical approaches and complex three-dimensional interventions. The overall effort and costs of preoperative CT data acquisition, intraoperative matching, and progression of fluoroscopy based intraoperative 3D imaging modalities has reduced the general use of navigation based on preoperative CT data. Nevertheless, there are some indications where CT-based navigation is required, including complex pelvic correction osteotomies and the resection of pelvic tumors [7–9]. Only 3D image information based on navigation can accurately and plastically reflect the complex anatomical relationships in these situations [10], and in these cases time requirements for the registration process are ignored. Intraoperative 3D fluoroscopy can still not be used for these indications because the image volume is limited to a cube of approximately 12 cm^3.

2.2 Intraoperative CT-based Navigation

Intraoperative CT scanners have been recently introduced, but due to their overall costs and the limiting space available in most operating suites, they have been established in only a few clinics. The navigation system is directly connected to a CT scanner so that the image data are directly imported and a registration process is not required. The CT data acquisition takes place either place after reduction or, in the case of screw placements, at the start of the operation, after which the navigated implant placement may take place.

Advantages of intraoperative CT scanners include improved image quality and scan volume compared to the intraoperative 3D fluoroscopy [1]. Disadvantages include the limited operation conditions for the CT scanner, the high logistic expenditure (i.e., the need for technical assistance and for manipulating and retaining the patient position during the scans), as the high cost for the purchase and maintenance of the equipment and for a specialized radiographic technician [11]. Even the installation of a CT scanner is frequently not feasible in existing operating theatres due to limited space and the statics of the building. Due to these limitations, this technology has not been widely adopted.

2.3 Intraoperative 2D Fluoroscopy

Integration of fluoroscopy in orthopedic navigation was introduced in 1999 and has been commercially available since 2000 [12]. Generally, data is imported from the navigated C-arm to the navigation system. This allows the simultaneous representation of up to four planes, which means a substantial improvement for the operating surgeon. This reduces annoying repeated c-arm movements during surgery and allows precise and simultaneous visualization of the surgical instruments in relation to the patient's anatomy in the all desired image planes.

The first surgical indications to employ fluoroscopy for orthopedic navigation were simple operation procedures, including the placement of distal interlocking screws and drilling of osteochondral lesions [9, 13–17]. 2D navigation principally allows precise drilling procedures of all osseous lesions, while potentially reducing the exposure to radiation and increasing the accuracy of the procedure [13, 18, 19]. In the last few years, however, the spectrum of indications where it is used has rapidly expanded and now includes the following:

- Application of sacroiliacal screws with representation in four levels (planes), anterior-posterior (ap), inlet/outlet and sacral. This navigation technology depends on the quality of the primary images, especially in obese patients or patients with intestinal gases.
- Placement of pedicle screws (simultaneous image presentations of the spine ap, lateral, and pedicle axial left/right).
- Navigated reduction of shaft fractures (Fig. 1).

- Navigated determination of the femoral antetorsion angle, fractured and contralateral side [20].
- Navigated high tibial osteotomy, including navigation of the osteotomy and determination of the mechanical leg axis [21–23].
- Ventral and lateral spinal interventions and spondylodesis

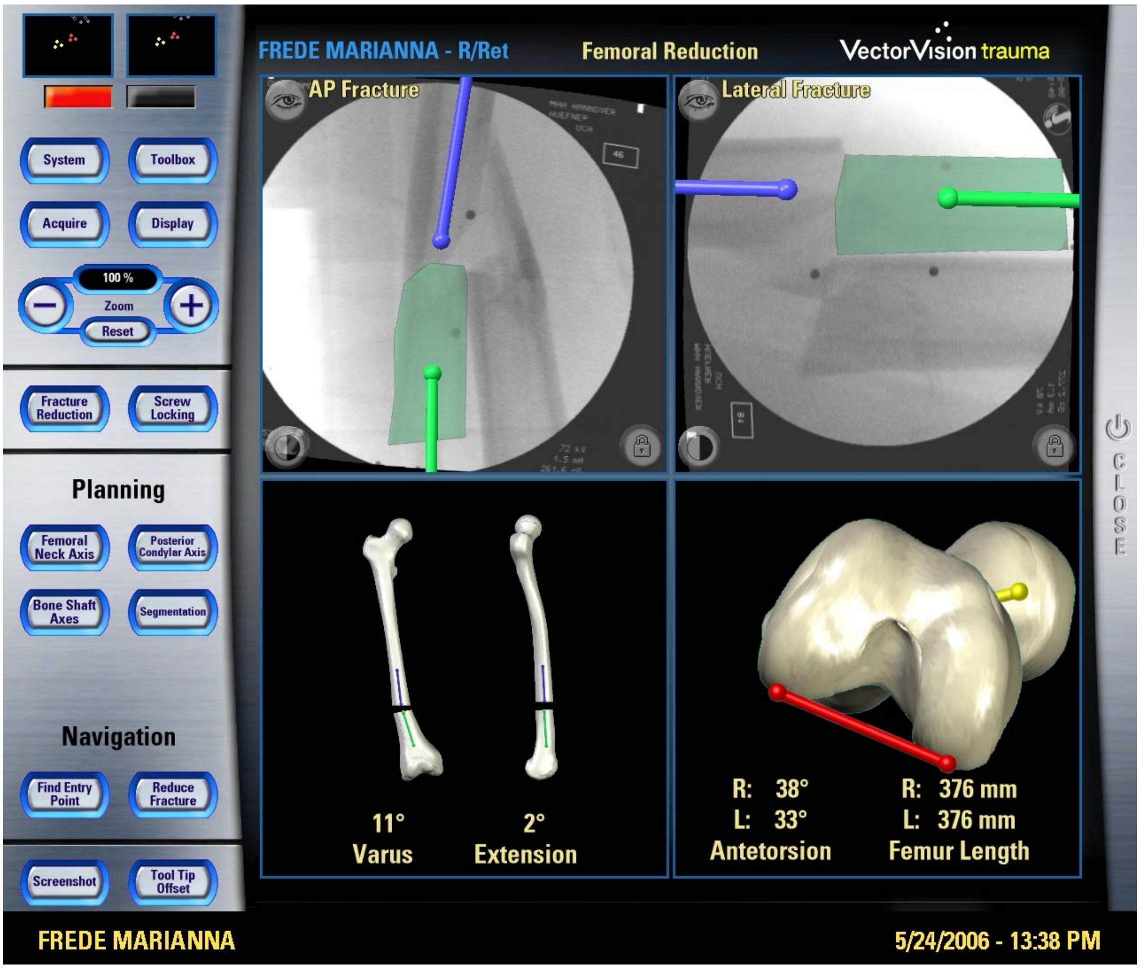

Fig. 1 Navigation screen of a femoral fracture reduction and anteversion module. The acquired fluoroscopic images allow for the dynamic visualization of the reduction process in ap and lateral positions without further intraoperatve radiation (upper two images). Further control of femoral anteversion can be achieved bilaterally while comparing the injured to the uninjured site (lower right image).

Recent femoral nailing and antetorsion modules allow for the first time the possibility of navigated reduction of femoral shaft fractures including the reduction of post-operative rotation differences [20]. By simultaneous representation of the neck of the femur axis and the posterior condylar plane relative to the femur shaft axis, the physiological antetorsion of the contralateral side can be measured and become the template for the fractured side. In addition, non-invasive referencing bands attached to the thigh are now being tested to measure the healthy side [24]. This avoids invasive techniques for fixing the reference markers. In clinical practice, the module is not frequently used because the logistic expenditure is currently very high and is not only become a routine procedure; however, further advances and applications are expected.

2.4 Intraoperative 3D Fluoroscopy

This 3D technology is based on a motorized self rotating c-arm (Siremobil [Siemens] or 3D Vision [Ziehm]) and has been used clinically since the beginning of 2003. It offers for the first time the possibility of implementing intraoperatively acquired 3D image data in the navigation system without a CT scanner. The combination of 3D reduction control and following navigated implant placement seems be useful [9, 13, 18, 25, 26]. Currently, this technology is regularly used for the following indications:

- Spine surgery: pedicle screw application
- Diagnostic or therapeutic drilling, for example, tumor biopsies, osteochondrosis dissecans, and osteoid osteoma (Fig. 2 and 3)
- Screw osteosynthesis in the pelvic ring (sacroiliacal screws) or the acetabulum (anterior column screw)
- Generally, all demanding screw applications during osteosynthesis

Fig. 2 Intraoperative setup for 3D fluoroscopy-based drilling of an osteochondral lesion of the femur condyle. A navigated drill combined with a navigated drill sleeve allow for an accurate positioning of a 3.2-mm drill bit. The reference marker is fixed to the distal femur.

Fig. 3 Navigation screen during the 3-D fluoroscopic drilling. Shown are a conventional fluoroscopic image and a secondary ceiling-mounted flat panel monitor. The nurse can easily use the touch-screen monitor.

The 3D c-arm and navigation system usually require a X-ray-permeable full carbon fiber table to allow rotating c-arm images without metal artifacts from the operating table or other metal materials.

However, the following important limitations of this new technology have been identified.

- The maximum scan volume is limited to 12 cm^3.
- The image quality is lower than in CT. Therefore, this technology is mostly used in surgery of the extremities. This difference is more even more evident for the application of implants or instruments.
- The scanning procedure itself requires training to avoid intraoperative complications and to produce accurate scanning results.

2.5 Precision in Orthopedic Navigation

Published reports and product information indicate that the precision of a navigation system is generally within 1 mm and 1 degree [27, 28]. This precision can be influenced by the surgeon at the following points:

- Camera system
- Reference marker
- Registration process

2.6 Camera System

The general precision of the camera system, including both active and passive systems, is 1 mm and 1 degree [27, 28]. Navigation systems require an optimal and free visual angle (line of sight) between the camera and the reference marker. Specified setup positions for the complete navigation system have been described for all indications by the manufacturers and the users. Optimal positioning and helps avoid complicated and time-consuming intraoperative reinstallations and movements of the navigation system. The optimal distance between the camera and the reference marker has been described to be between 1.5 and 5 m, although the ergonomic arrangement in the operating room also includes defined positioning of the patient, the nurse, the navigation system, and the other related instruments.

2.7 Reference Markers

Cable-based reference markers have mostly replaced by cableless systems. Active marker system are based on the ability of the marker to actively send out infrared signals, whereas passive systems are based on the reflection of infrared signals from the navigation camera. Intraoperative problems occur by contamination of the reflecting materials with patient blood or other fluids; therefore, the contamination must be removed [1] (Fig. 4). In addition, rigid fixation of the reference marker to the extremity or osseous trunk is especially challenging. Consequently, inaccuracies might go unnoticed during surgery and causing false results [29, 30].

Recent studies have shown differences in the osseous stability of various reference marker fixation systems. Significant differences (up to 70%) in the minimal force for loosening of the markers have been found between various systems [31]. For some anchorage systems, monocortical osseous fixation can achieve the maximal force of fixation.

2.8 Registration Process

The registration process describes the precise definition of a correlation between the relevant patient's anatomy (e.g., leg axis or osseous pelvis) and the navigation system. For trauma-associated indications, most c-arm images are imported intraoperatively from a referenced 2D or 3D c-arm. For CT-based modalities, preoperative image data is transferred to the navigations system, and a complete matching process between patient's anatomy and the CT images must be performed. Recently, image-free technologies have been incorporated into navigated high tibial osteotomies, whereas image-free registration has been in successful in all endoprotshetic indications for several years [11, 32]. Kinematic surface morphing algorithms allow for adequate image-free registration of the lower extremity axis including the hip and knee joint [22].

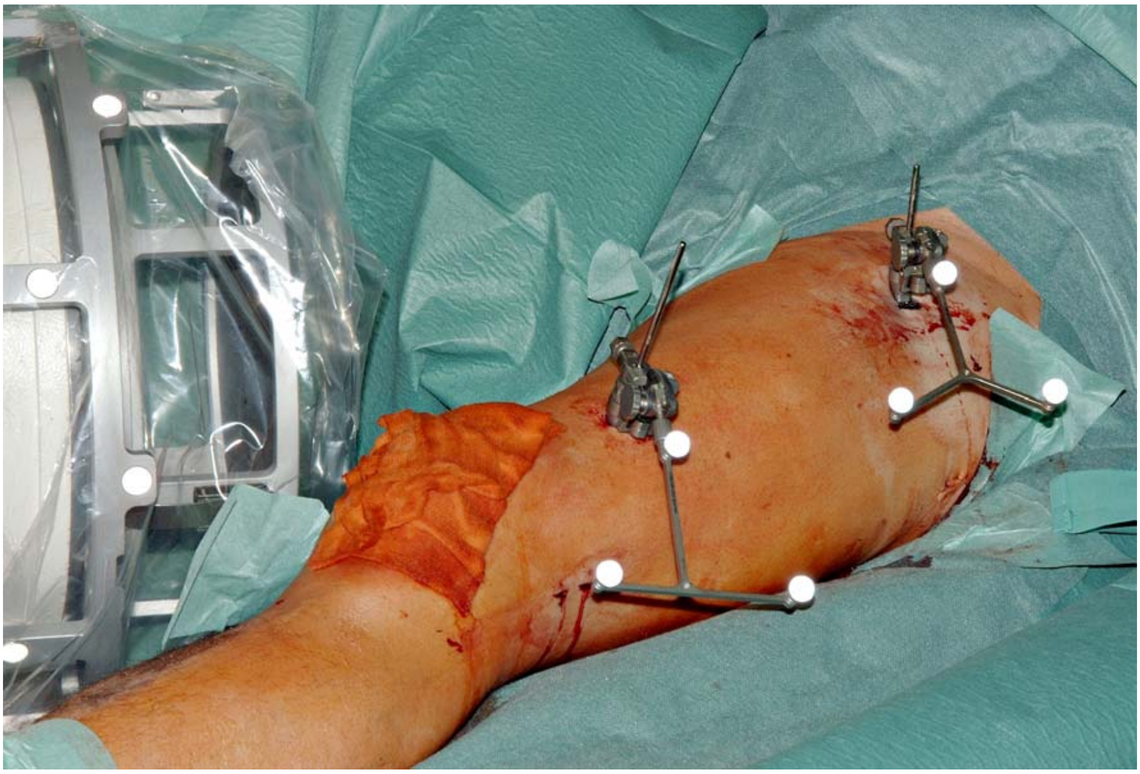

Fig. 4 Stable fixation of the reference markers, in this case at the thigh for a navigated reduction of a femur fracture, is necessary to ensure a valid navigation process. The markers require a clear reflecting surface for a correct communication with the camera system.

2.9 Discussion

Acquisition of a navigation system in orthopedic trauma surgery should reflect certain considerations. All modules must be selected (e.g., trauma and total hip and knee replacement). 2D fluoroscopy is regularly employed for numerous orthopedic trauma applications. CT-based navigation is most well studied navigation technology, but its use has declined because it involves a time-consuming intraoperatively registration process and because of advancements in intraoperative 3D fluoroscopy. Furthermore, for most fracture patterns, preoperatively acquired CT data does not represent the actual intraoperative situation after reduction. CT-based navigation has recently become an alternative for some individual cases, such as tumor resections or specific corrective indications. Navigation using 3D fluoroscopy appears to be ideal for combined reduction control and navigated implant placement in the extremities, pelvis, and spine, although the first controlled studies are just being completed, and prospective studies have not yet been carried out.

Fig. 5 Navigation-based reduction of a complex intraarticular radius fracture. Preoperative CT scans can be used to control the fracture patterns intraoperatively. The navigated pointer is used to track different fracture patterns.

Future applications of navigation technologies include the navigated reduction control of complex articular fractures with the help of preoperatively collected CT scans of the uninjured site. This allows the step-by-step visualization and dynamic reduction of several fracture patterns (Fig. 5). Prior to the selection of the navigation system, including the module and imaging modality, the orthopedic trauma surgeon should take practical courses or training in an experienced navigation center. So far, most prospective studies have focused on navigated total knee arthroplasty, and additional prospective studies on the use of navigation technologies in orthopedic trauma care are needed.

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