6 Computer-assisted Minimally Invasive Spine Surgery

State of the Art

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6.1 Introduction

With the advent of precise pre- and intraoperative imaging means, the development of sophisticated image data visualization, and the accessibility of submillimetric, real-time tracking of objects in space, surgical navigation systems have been created that aim at enhanced surgical accuracy and ultimately improved clinical outcome [3, 6, 9, 13, 17, 20]. Numerous studies have shown the superiority of computer-assisted versus conventional instrumentation at different levels of the spine regarding accuracy and thus potential safety [4, 14, 24, 25]. However, this technique has been less successful in contributing to the reduction of intraoperative invasiveness, although this aim has been anticipated by most of the pioneering authors [13, 17, 20]. It is the aim of this article to outline the basic principles of computer assistance for spine surgery, which will help the reader to understand why navigated interventions must be invasive in the first place. In addition, efforts towards less and minimally invasive procedures of the past and current research will be presented and discussed.

6.2 Computer-assisted Orthopaedic Surgery

The idea of computer-assisted orthopaedic surgery is to replay surgical action on a computer monitor in real-time providing a valuable visual feedback to the operating surgeon. This concept is, therefore, comparable to a GPS satellite navigation system installed in a car, which constantly displays the car's location on a street map. In order to generate such feedback during spine surgery three tasks have to be fulfilled by a spinal navigation system: (a) an image or a set of images of the spine has to be provided serving as the "map" of the patient, (b) the spatial location of all important instruments has to be measured constantly in three dimensions and in relation to the operated bone, and (c) the relative instrument position has to be transferred into image space to enable visualization at the correct location.

6.2.1 Image of the Spine

Theoretically, any two- or three-dimensional image of the spinal anatomy may be used as the "patient map". However, the need to display the bony structures clearly and to process the image data digitally by computer software made preoperative CT scans and intraoperative fluoroscopic images the modalities of choice in current navigation systems. Preoperative imaging allows for careful inspection of the clinical problem to be treated as well as for precise planning of the intended intervention. On the other hand, relying upon preoperative CT scans for navigational feedback may be non-optimal when the corresponding shape of the operated vertebra is about to be altered considerably during the operation, for example, in cases of tumour removal or fracture reduction. Moreover, a suitable digital dataset in the form of a preoperative CT scan may not be available, and the irradiation that goes along with a new CT acquisition may not be justifiable for a particular case. Intraoperative fluoroscopy may be used as alternative imaging in these situations. This technique allows the capture of conventional fluoroscopic images with the help of the navigation system and uses them to provide navigational feedback to the surgeon. Since the images can be reacquired intraoperatively, this technique may also be applied in cases when preoperative CT scans no longer reflect an altered intraoperative situation. This advantage, together with the obsoleteness of manual registration (see below), often outweighs the disadvantage that the absence of a preoperative dataset does not allow detailed computer-aided planning prior to the intervention. Another disadvantage of fluoroscopy-based navigation (the missing third dimension in conventional two-dimensional projective fluoroscopic images) has been overcome recently by the introduction of a new three-dimensional fluoroscope (see below).

MRI datasets have so far failed to become frequently used as navigational images in computer-aided spine surgery. The inherent geometric distortions together with the difficulty to create three-dimensional representations of the bony anatomy in an easy fashion have

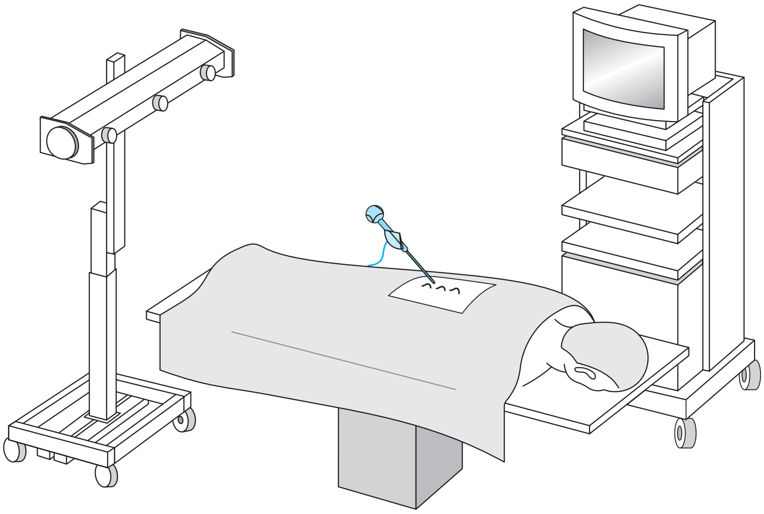

Fig. 6.1. Intraoperatively, a spinal navigation system observes surgical instruments and the operated vertebra with the help of an optoelectronic camera. The resultant position data are displayed on a computer monitor in real-time

prevented MRI becoming regularly used in spinal navigation. Research groups have looked into the fusion of preoperative CT and MRI scans [22] to enable the use of information from both modalities simultaneously during computer-assisted surgical (CAS) application. Again, remaining questions and difficulties have so far hindered the widespread use of these approaches.

6.2.2 Measuring Instrument Position

To exactly determine the current position and orientation of instruments in the hand of a surgeon in relation to the treated vertebra requires the precise and contactless tracking of both bone and tool. Surgical navigation systems follow the principle of rigid bodies, i.e. each observed object is regarded as undeformable and of known shape. The tracking of such an object can then be simplified to the tracking of at least three non-collinear points that are rigidly attached to it. This theoretical principle is realized by means of infrared light-emitting diodes (IREDs) or infrared light-reflecting markers that are observed by a camera system. IREDs need external power to actively emit light and, therefore, most active navigation systems require instruments to be connected via cables. In contrast, passive markers reflect light that originates from an infrared light source integrated in the tracking camera and that illuminates the camera's entire field of view. In both cases, direct line-of-sight between the camera system and the observed IREDs/markers is mandatory.

Alternative measurement technologies, such as electromagnetic tracking, have not been successful in the past due to large inaccuracies [3].

6.2.3 Displaying Instrument Position

To display a tracked instrument at its correct location with respect to the treated spinal section, it is necessary to also track the operated vertebra. For this purpose, a so-called dynamic reference frame or dynamic reference base (DRB) [20] is attached to the spinous process (Fig. 6.1). Technically, this DRB establishes a local coordinate system (COS) that is affixed to the rigid structure of the vertebra, and instruments are tracked with respect to it. Real-time navigational feedback is then provided by transferring the measured three-dimensional instrument coordinates from the DRB-COS into image space (Fig. 6.2). The mathematical matrix that allows this transformation is determined by a registration step. For preoperative CT scans this task is completed intraoperatively and involves the surgeon acquiring relevant structures on the bony surface of the operated vertebra [19]. In contrast, fluoroscopic navigation does not rely on interactive digitization. Instead, the imaging device is calibrated preoperatively, which enables the intraoperative registration to be an inherent and automatic procedure [11].

6.3 Minimizing Invasiveness

Orthopaedic surgery is treating structures that are usually located deep inside the human body. As a consequence, three reasons can be identified why it has to be invasive in the first place [15]:

1. The surgeon needs to have visual access to the operation field. Such access is usually gained by exposure of the operated structures.

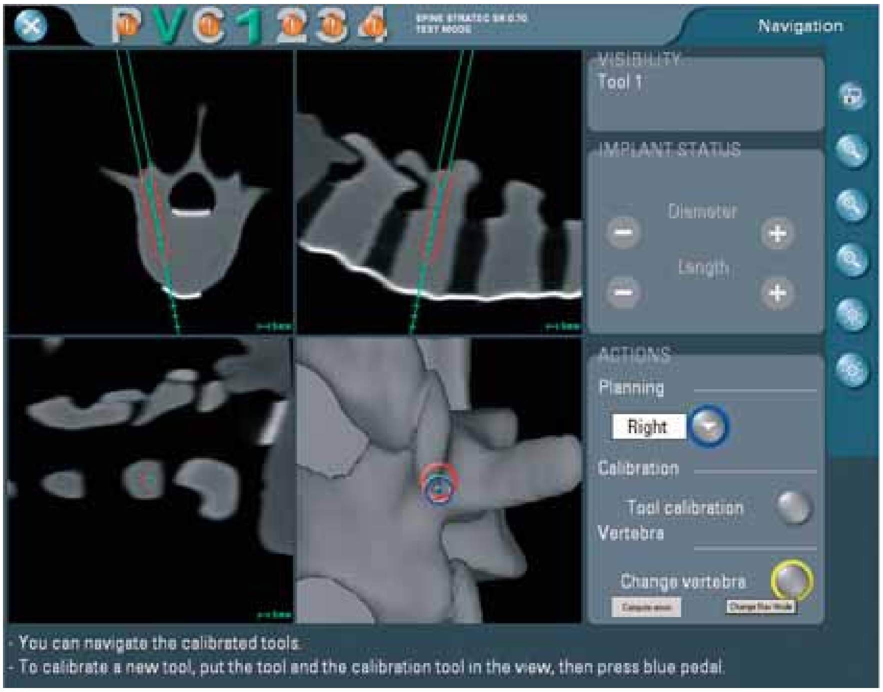

Fig. 6.2. During CT-based navigation, the current instrument position is presented in relation to a preoperative CT scan. The optimal position of this L4 pedicle screw (*red contour*) has been planned preoperatively and serves as the target to be reached by the navigated pedicle awl

2. Surgical instruments need to act on the bone. Tools such as awls, drills or probes require direct physical contact with the bone as well as a certain working volume.
3. Many orthopaedic interventions include the placement of implants such as screws or rods. The delivery of these devices can only be accomplished in an invasive manner.

It is obvious that invasiveness due to reasons 2 and 3 can only be reduced by improving instruments and implants, and today manufacturers of medical technology have advanced and optimized their products to a very high level.

Computer assistance could be seen as a means to target reason 1 of invasiveness. The real-time feedback provided on the monitor of a navigation system represents considerable and valuable details about surgical action and might thus allow for smaller incisions. This potential has been foreseen by many of the pioneers in computer-assisted surgery [13, 17, 20]. However, the enthusiasm and optimism of these early users did not turn out to become common reality. Consideration of the additional elements, described above, that are required for the application of surgical navigation explains this apparent discrepancy. Referencing of the operated vertebra is a must [8] and up to now requires the stable attachment of a DRB to the spinous process. When using preoperative CT scans as the navigation basis, intraoperative registration necessitates access to a considerable area of the bone surface in order to digitize anatomical landmarks or characteristic bony structures.

Up to now, research efforts have been focused on alterative registration methods, and the development of fluoroscopy-based spinal navigation (Fig. 6.3) was surely catalysed by the vision to implement registration as a preoperative calibration step rather than requiring interactive and error-prone data acquisition as an intraoperative procedure. With the help of such a fluoroscopy-based CAS system, Foley et al. [5] could demonstrate that even two-level fusions could be carried out through stab incisions when a dedicated minimally invasive rod placement device was used. Besides cosmetic advantages of the resulting smaller scars, the authors point out that the muscular apparatus in the operated region can be left almost completely intact, which should eventually result in better recovery times.

For CT-based navigation, several alternative registration methods have been proposed to improve registration accuracy, ease the intraoperative registration procedure, or allow for registration in a less invasive manner. Placing fiducial markers to the patient as "artificial anatomical landmarks" prior to image acquisition is a common technique for navigated cranial surgery [1]. Such markers [27] make very strong signals in the acquired CT scan and may be identified easily. Moreover, digitizing them intraoperatively on the patient with high precision is a trivial task that can be performed reliably and fast. To further optimize this concept, Lund et al. evaluated a combined marker and DRB placement approach [16]. Before the CT scan, a small

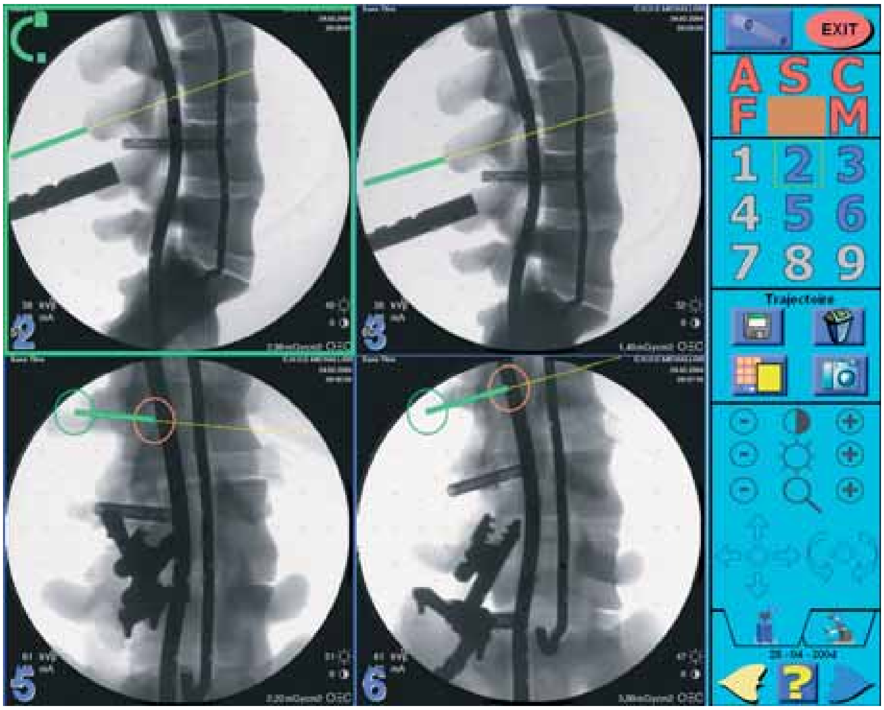

Fig. 6.3. During fluoroscopy-based navigation, instrument position is projected into several two-dimensional fluoroscopic images at the same time. The two circles at the tip (*orange*) and end (*green*) of the instrument indicate the orientation of the tool relative to the image plane

clip was affixed to the spinous process (Fig. 6.4) under local anaesthesia and the wound closed again. The clip housed three spherical titanium markers at positions that were exactly known to one another. In addition, it featured a highly precise connection into which the DRB could be placed in a well-defined orientation. After CT scanning, the marker spheres were identified in the image data and the operation was started. The placed clip was exposed again and the DRB attached (Fig. 6.5). Thanks to the previously measured marker location the spatial relationship between reference base and image data could be calculated automatically without any additional interactive and invasive landmark digitization on the patient. The authors used their method during two cases of pedicle screw placement in the lumbar region and report sufficiently accurate feedback by their navigation system. However, the additionally required surgical procedure to place the clip to the spinous process was found to expose the patient to unacceptable discomfort. Moreover, the logistical and financial efforts caused by this preceding operation were estimated to be too exhaustive.

Fig. 6.4. This base part of a prototype dynamic reference base is mounted to the spinous process prior to CT data acquisition. The three high-precision titanium spheres help registering the device with the image data in an automatic way

Recently, research has focused on non-invasive registration methods based on intraoperative ultrasound [18]. From a technical point of view, both A-mode (amplitude mode) and B-mode (brightness mode) ultrasonography using calibrated and tracked ultrasound probes are methods that can yield the three-dimensional locations of bony surface points assessed through layers of soft tissue. In practical applications, however, this non-invasive digitization is not trivial. For A-mode ultrasound a single sound pulse is sent and received along one acoustic axis, comparable to the sonar depth measurement of a ship. For the reflected sound signal to be detectable by the probe, the explored

Fig. 6.5. Intraoperatively, the upper part of the dynamic reference based is mounted. Thanks to its precise fitting to the base, it facilitates automatic registration of the preoperative CT scan with the intraoperative setup

bone surface must be oriented horizontally. This limits the applicability of A-mode ultrasound at the spine to the transverse processes and small areas of the facet joints and the spinous processes. B-mode ultrasound (Fig. 6.6) in contrast is easier to use intraoperatively because it scans a fan-shaped area rather than a single axis. However, the resulting two-dimensional images are noisy, and the automated detection of bone contours is a challenging image-processing task. As a consequence, only experimental results are available [2] for the application of this technique to anatomical areas other than the spine.

6.4 Further Clinical Applications

The technical challenges outlined above indicate why CAS techniques have so far failed to make minimally invasive procedures state-of-the-art in spine surgery. Nevertheless, a number of authors have succeeded in avoiding large surgical approaches thanks to image-guided methods. Some have already been mentioned in the previous section. In addition, there are several reports of the use of navigation technology applied during procedures that are carried out in a minimally invasive manner even when no navigational support is applied. The CAS system in these cases is used to increase safety and precision and to decrease radiation exposure to the patient and surgical staff. An example is intradiscal electrothermal therapy with the help of fluoroscopy-based navigation [21]. Using C-arm images for nav-

Fig. 6.6. In this experimental setup the use of a tracked B-mode ultrasound probe for registration data acquisition is evaluated

igation appears to be a generally accepted multipurpose method that authors try to apply to a variety of surgical approaches to the spine, including ventral fracture stabilization [28] or disc replacement [23].

Recently, an isocentric motorized fluoroscope was introduced [10]. It performs an automated 190° rotation during which it acquires a series of 100 two-dimensional images. From these data, a three-dimensional dataset is reconstructed intraoperatively that is similar to a CT scan. Since the data are generated with a calibrated and tracked imaging device, there is no need for manual registration, and navigation within the images is possible immediately after image generation and transfer to the navigation system. Although the use of this fluoroscope is not limited to the spinal area, several authors have already presented very promising results with it in applications such as pedicle screw placement [7], kyphoplasty [26] and other types of spinal instrumentation [12].

6.5 Discussion and Conclusion

The first decade of spinal navigation systems tried to improve the precision of implant placement and the reliability with which surgical interventions can be carried out while at the same time often reducing intraoperative radiation exposure. Very often, however, these advantages had to be paid for with the prohibition of minimally invasive procedures or even led to increased invasiveness when compared to the corresponding conventional techniques. Recent research efforts now try to enable spinal navigation in a less invasive manner. CAS systems have been utilized to provide additional visual feedback during existing minimally invasive procedures. Intraoperative image acquisition, both using two- and three-dimensional modalities, require only a DRB to be attached to the bone eliminating the need for large-scale bone access that is a prerequisite for the manual registration of preoperative image data. Last but not least, alternative imaging methods are in the focus of current research to evaluate their potential in non-invasive bone-contour detection. In any case, establishing procedures with minimized invasiveness will require combined research and development efforts by navigation system producers, implant manufacturers and surgeons in order to optimize each aspect of the process.

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