CT-based Navigation for Knees and Hips in Minimally Invasive Surgery

F. Langlotz, L.-P. Nolte

Introduction

The use of a surgical navigation system improves intraoperative visibility into the surgical situs and has therefore been believed to provide the means towards less or even minimally invasive interventions. However, these expectations have usually not been met during the experimental or routine application of navigation systems for total knee or total hip arthroplasty. In contrast, the increased accuracy and safety of this technology had often to be paid for with larger incisions, increased blood loss, prolonged operation times, or additional trauma. This article tries to highlight the reasons for this apparent discrepancy and summarizes current developments that aim at overcoming the dilemma. The basic principles and concepts of surgical navigation in the domain of orthopedics have been presented in detail before [1, 2] and will therefore not be covered by this paper.

Invasiveness of Surgical Interventions

The treatment of pathologies that are situated deep inside a patient’s body such as arthritis or other joint diseases requires the direct access to these anatomical structures. Established surgical approaches grant this access through superjacent layers of soft tissue. In general, three reasons [3] can be identified why orthopedic surgery has to be invasive in the first place:

- Instruments that are employed to treat pathologies need to have contact to the diseased structures. Such contact can obviously be realized in an invasive manner only.
- During total joint replacement, implant components need to be anchored into the bone, and these components need to be delivered to the anchoring sites. Any surgical incision for total joint replacement has to be of sufficient size to enable introduction of the required implants.
- Last but not least, visual feedback is essential for the operating surgeon, and the optic sensation is definitely one of the most important impressions that guarantee optimal intra-operative performance of the surgeon.

Obviously, optimizing surgical skills and the development of dedicated surgical approaches [4] are means to minimize invasiveness as induced by the first reason given above. Implant manufacturers are constantly advancing their instruments and implants to enable less invasive techniques of arthroplasty [5]. Improving the insight into the surgical action that takes place in the situs is potentially a third way to reduce the invasiveness of surgical interventions while maintaining precision. Although mechanical aiming devices have been proposed as tools to achieve this goal, their accuracy has been highly questioned [6].

Computer Assistance to Reduce Invasiveness

With the introduction of CT-based computer-assisted navigation systems in the mid-nineties of the last century [2] a technology became available that was believed to pave the road for less invasive or even minimally invasive surgical procedures [7–9]. However, the enthusiasm and optimism of these pioneers did not turn out to become reality except for a very limited number of selected applications [10–12].

This apparent discrepancy lies in the additional steps that are required for CT-based navigation [1]. The unavoidable relative motion of the operated bony structures needs to be compensated [13] by means of one or
more so-called dynamic reference bases (DRB) [9]. These devices require a rigid and stable connection to the bone to be operated on. In the case of total hip replacement one DRB is affixed to the pelvic crest [10] and/or the femur [14] through the existing (Fig. 11.1) or even additional incisions. During total knee replacement, DRBs are inserted into the distal femur and the proximal tibia [15]. Early implementations of surgical navigation for TKR required even the placement of a DRB to the pelvis [16, 17] in order to enable precise acquisition of the mechanical axis of the limb.

Using any pre-operative image data such as a CT scan as the virtual object of a navigation system requires a registration between the patient's anatomy and this image [1]. Many mathematical methods have been presented [18] to achieve registration between the underlying coordinate spaces, but all early implementations relied upon the direct digitization of features such as anatomical landmarks on the bony surfaces of the operated structures. It is obvious that such a data collection using a tracked pointer [9] prohibits the introduction of minimally invasive procedures.

In order to overcome the described obstacles, alternative, less or non-invasive methods for registration and/or referencing were required and a large variety of different approaches have been proposed.

**Alternative Ways of Registration**

Intra-operative and interactive registration of the patient's anatomy with a pre-operative image-data set is obviously not required when using intra-operatively acquired image data for navigation purposes [14, 19]. However, this aspect of computer-assisted total knee and hip arthroplasty is beyond the focus of this article and shall therefore not be addressed.

The probably most obvious approach to minimally invasive registration is to use a different method of point-data acquisition which will eventually permit the established mathematical algorithms to be applied that have been developed for pointer-based registration. Calibrated ultrasound has been proposed as a means to accurately determine deeply located bone contours. First applications using A-mode ultrasound probes in the context of navigation were presented for neurosurgical interventions [20] and are still being applied in the area of the skull [21]. However, inherent difficulties proved this method to be non-applicable during orthopedic surgery, in particular when applied for the registration of deep structures such as the pelvis or femur [22]. Especially the linear reflection of the sound pulse causes problems, since it requires the ultrasound probe to be oriented perpendicularly to the surface to be assessed. B-mode ultrasound technology overcomes this disadvantage. The acquired images are two-dimensionally and show bone boundaries that can be determined. As a result, the location of points along such a surface line may be fed into a registration algorithm. However, B-mode ultrasound images are usually very noisy, and the automated determination of bone contours is non-trivial. Tonetti et al. [23] therefore presented an approach involving the interactive intra-operative segmentation of the acquired ultrasonic images. They could demonstrate a sufficient accuracy of their approach when used at the pelvis. The problem of reliable, automatic bone-contour detection from B-mode ultrasonography has meanwhile been solved experimentally [24, 25] as shown in Fig. 11.2, but has not been used clinically in a broad way so far.

Another method to acquire the locations of points without accessing them directly is provided by calibrated C-arm fluoroscopy [26]. If two or more two-dimensional projection images are acquired of an anatomical location from different directions, three-dimensional locations can be calculated with the help of a triangulation approach. The spot to be reconstructed is identified on each of the images resulting in a set of lines in 3D space along the respective projection direction. The associated 3D point can then be found at the intersection of these lines. This method involves the interactive
digitization of landmarks in the acquired images, which can be accomplished in an operating-room-compatible manner [14]. However, this procedure is rather time-consuming and tiresome. It is thus difficult to be promoted for the acquisition of larger quantities of points as needed for exact intra-operative registration.

The logically next step in the development of fluoroscopy-based registration techniques was the automated feature extraction from the recorded images to enable a less cumbersome intra-operative application of this technology. This “fluoromatching” method has been implemented for navigated spinal surgery. First, the surgeon needs to specify the vertebra to be registered. The associated CT data is then presented in a lateral and anteroposterior view, and corresponding fluoroscopic images need to be acquired with the DRB in place. To initialize the registration algorithm, the surgeon manually aligns both images with the CT views, and the system tries to refine this coarse registration. Despite the considerable amount of interactivity that this approach requires, the concept is still lacking perfect reliability [27].

**Alternative Ways of Referencing**

Referencing is essential for any kind of surgical navigation [13]. It is of particular importance when pre-operative images are used as virtual objects since there is no correspondence between the patient’s position during image acquisition and during the actual operation. Robotic-assisted surgery achieves referencing by means of a mechanical link between the robot and the bone to be operated on [28] or by mounting a miniature robot directly onto the bone [29]. These approaches often result in an increased invasiveness when compared to the respective conventional techniques. However, the placement of dynamic reference bases during total knee and total hip replacement also involves steps of increased invasiveness in the very most cases. DiGioia et al. anchored the DRB through a small additional incision “near the wing of the ilium” [10], while DRB fixation during total knee replacement is usually possible through the standard surgical approaches.

Hardly any research has been performed with the aim to reduce the invasiveness of DRB placement. Lund et al. presented a prototype system for navigated spine surgery [30] in which they reduced the incision for fixing the reference base to a minimum. However, a portion of their reference base (Fig. 11.3) had to be implanted.
prior to CT scanning, i.e. pre-operatively, which was found to be unacceptable for routine use. Apparently, there is no technique available for referencing of the operated anatomy that does not rely upon the physical attachment of a reference base. Hence, approaches towards less or minimally invasive referencing have to focus on the development of associated fixation techniques for DRBs or come up with entirely different solutions. If, for instance, ultrasound registration could be realized in real-time and in a fully automatic way, the resultant matching transformation could be constantly re-calculated during navigation, essentially eliminating the need for any separate referencing.

Conclusions

CT-based surgical navigation provides means to improve visual perception during total joint replacement. In this sense, the technique has the potential to contribute to a reduction of the invasiveness. Current approaches, however, usually require invasive access to the operated bone for the acquisition of registration data and the fixation of dynamic reference bases. A major focus of research was and is the desire to implement alternative registration methods. Referencing – up to now – has received less attention potentially due to the absence of complementary ways to compensate for motion of the patient relative to the tracking system. At present least invasive navigation support can be achieved using computer-assisted systems that use intra-operative [31] rather than pre-operative image data. However, one important positive aspect of CT-based navigation must not be underestimated: only a three-dimensional scan of the pre-operative pathologic situation of a joint allows planning the operation sterically and enables the sophisticated simulation of the post-operative performance of the prosthesis [10].

References