Registration Techniques in Computer Assisted Orthopedic Surgery (CAOS)

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Introduction

A couple of years ago, before the introduction of GPS systems in nearly every car and before the widespread availability of mobile phone networks in eastern Europe, I was visiting some friends in a foreign country. On the way home, it began snowing lightly, and for some odd reason, the snow sticked to nearly every traffic sign, so it was impossible to read the guideposts, which told us the correct direction to Germany or at least the names of the villages we passed. Although we had the best road maps and we stuck only to major roads, at one point we had to realize, that we were lost. Since our language skills were approaching zero, mobile phone was not working, the sun had already set and we had no compass, there was absolutely no possibility to determine our present position and so we had no chance to get home, until the snow melted away the next morning and we were able to read the guideposts again.

This short story demonstrates one major problem of navigation: There is the real world (the foreign country's streets and cities) and there is a virtual model of this real world (which is the roadmap, in our analogy). It is the navigator's task, to correlate these two spaces, so that he will know where the object of navigation (his car) is and where he has to lead it.

In computer-assisted surgery, the process of referencing a virtual model (e.g. a CT scan) to the real world (the patient) is called "registration". During this process, the coordinate systems of both, the virtual and the real object, are digitized in some way, so that the navigation system is able to recognize them and to put them in relationship to the navigation system's intrinsic coordinates. By many authors, registration is recognized as the most crucial process in computer assisted surgery (1). Registration has to be performed individually for every surgery, and any imprecision will carry forward throughout the whole navigation process.

> Registration is the process of linking the coordinate systems of the navigation system, a virtual object (e.g. a medical image) and the real patient.

During the technically driven development of navigation systems, many different registration techniques have evolved. In principle, they can be grouped to either image-based registration techniques or image-free techniques.

By using image-based registration techniques, a re-

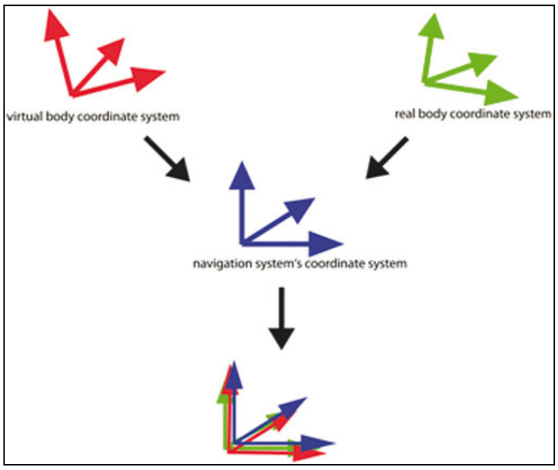

Figure 1: The process of registration matches the three coordinate systems of the virtual model (red), the real object (green) and the navigation system (blue).

corded medical image will somehow be matched to the real surgical anatomy. The advantage implies a precise presentation of the surgical intervention in relationship to anatomical structures, which is crucial for instance in pedicle screw placement or SI-screw placement, where a deviation in the millimetre range can lead to neural or vascular damage.

Image-free registration techniques will mainly reference to mechanical axes, which are defined by some pivoting and rotating maneuvers during registration. These techniques are used in cases, where a precise relationship to anatomical structures is of minor interest compared to a proper alignment in relationship to mechanical axes, mainly joint replacement or osteotomy procedures.

Image-based techniques provide anatomical precision, whereas image-free techniques provide predominantly precision of the mechanical axes.

Within these two groups, there are multiple different techniques, which all have their own advantages and disadvantages.

Image based registration

Nearly all of the commonly used medical imaging devices have been tested to support surgical navigation: Fluoroscope, CT, ultrasound, even MRI (2,3). During the last years, this parade has been supplemented by the introduction of 3D-fluoroscopes or the so-called O-Arm as hybrids of fluoroscope and CT.

Each of these devices has some specific attributes, which have an influence mainly on the two parameters image type/quality and time point of image acquisition. The importance of image quality is obvious: the higher image resolution and contrast, the better is the visualization of the anatomical structures. Depending on the device, we acquire 2D- or 3D-images. 3D-images add important information, namely the transverse cut, which is the most important view in many procedures in which navigation is used today.

The relevance of the time point of image acquisition becomes evident, if you look at certain unstable situations in trauma surgery: If the images are acquired before positioning of the patient in the OR or before reduction of a fracture, the anatomy may have changed significantly. If we stick to our car navigation allegory from the introduction, this is like driving with an older road map from several months ago – streets may have been redirected and new ones may have been built.

In newer technologies, image acquisition is done intraoperatively, and since the image devices can be localized by the navigation system, image acquisition and registration are done within a single step. This saves time and eliminates a manual registration process as a source of error. This is like getting a hyper-up-to-date satellite shot of your travel route – including your own car's position. So the navigator is relieved of the sometimes difficult duty of defining his own position by comparing street names on the map and in the real world.

Additionally, the intraoperatively acquired image shows the recent morphology after positioning the patient or reposition of a fracture. It is like the satellite photograph will show every recently erected construction site and current traffic jams, which were present on the time point of the start of the journey.

Different image based techniques mainly differ in terms of image type, image quality and time shift between image acquisition and registration.

CT based techniques

CT based registration techniques were the first to be used in computer assisted orthopedic surgery (4). CT scans provide a high tissue resolution with a good bone / soft tissue contrast, which helps to determine the intraosseous position of a surgical instrument or implant.

The commonly used navigation systems utilize preoperatively acquired CT images (so called "canned" data), which are to be registered to the navigation system coordinate system in a certain matching procedure during the operation. The major problem with this method is the time-shift between image acquisition and the surgical procedure. After the CT scan, which is usually done in supine position, the patient will be carried to the OR, sometimes with a significant delay. He might then be positioned in prone position (e.g., for posterior spine surgery) or a broken bone (e.g., the pelvis) might be reduced to its normal position. So, the anatomy might have changed between image acquisition and intraoperative referencing. Therefore, pre-op CT based navigation can only be performed on structures that are not subject to change during these maneuvers. For instance, if you plan to navigate an unstable spinal fracture, you should reference each vertebra on its own to compensate for any changes of the anatomy.

But, there are not only disadvantages attributed to this technique. Most of the diagnoses, which may profit from a navigated surgery, usually require a preoperative CT anyway for setting the indication and surgical technique. The herein acquired images may be used for navigation, if they are recorded in a suitable manner. This helps reducing radiation dose for the patient and the surgeon. Another point is the possibility of preoperative planning. Additionally, most of the CT based navigation systems do offer a pre-op planning option for distinctive setting of implants like pedicle screws or joint prostheses. The trajectories of these preoperatively planned implants may be transferred to the intraoperative navigation system and displayed on the virtual reality screen. The registration techniques, that use intraoperative imaging, may offer a planning solution as well, but the planning process must take place during the operation - which is easy in simple cases, but possibly not the best environment to discuss really difficult cases.

Let's go to our travelling analogy again: Using a somewhat older map ("canned data"), that you possess some weeks before the beginning of the journey, will enable the navigator to calculate the fastest or easiest way to the destination – and to discuss with the other participants intensively.

Concerning the referencing process itself, there are several different ways to match the previously recorded images with the intraoperative anatomy. All of them have their own advantages and disadvantages.

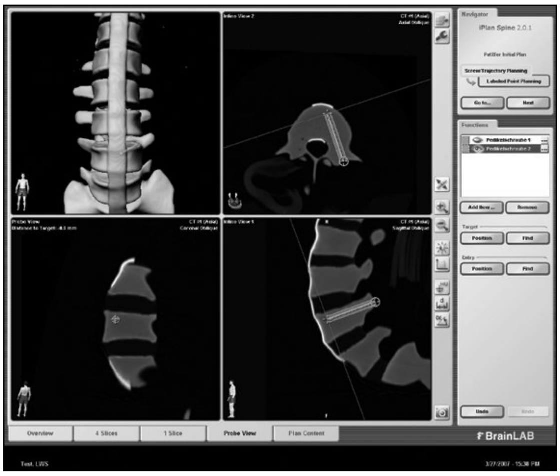

Figure 2: Preoperative planning option in CT based registration. The light grey bar indicates the trajectories of a pedicle screw, which will be intraoperatively displayed on the navigation screen.

Paired point matching

Paired point matching was the first registration technique to be used in navigation procedures (5). It is mostly used in CT based matching, but may be used in other imaging techniques as well. From the preoperatively acquired CT image, a 3D-surface reconstruction of the bone is calculated. In this surface view, at least 4 points, which are easy to be recognized intraoperatively, like the tip of the spinous process or a crossing of two bone crests, are determined and saved during the planning procedure.

Intraoperatively, these points have to be re-identified in the surgical situs and digitized using a calibrated stylus. These digitized points are then overlapped with the corresponding points in the virtual model using a least-squares optimization algorithm until the position with the least difference between the virtual and the real object's coordinate systems are found (for details, see (6)).

Since it requires only a few points to be identified in the situs, it is a simple and quick technique. A disadvantage is the risk of a diminished accuracy, if one or more of the four points are registered inexactly. The exact identification of the previously defined landmarks can sometimes be difficult and even impossible, if the landmarks have been removed during the procedure (e.g. a laminectomy) (2). To avoid this, it is strongly recommended to choose landmarks, which are easy and explicit to identify in the image as well as in the surgical site. A thorough preparation of the surgical situs is a prerequisite, since small amounts of soft tissue covering the bone can lead to inaccurate registration results.

Furthermore, the accuracy can be improved by choosing reference points, which span a large volume. This is in contrast to the goal of minimal invasiveness, because a further opening of the surgical site might be necessary.

Paired point matching consists of "pairing" preselected landmarks in the image and the surgical situs. It is simple, quick, but the accuracy might be low.

Surface matching

A further development in registration techniques is the surface matching. This technique also requires a 3D surface shaded display of the preoperatively acquired image. But, instead of determining unique reference points in the image first and then trying to match them with the surgical site, the surgeon starts to register a "cloud" of points of free choice on the bone surface. The navigation system will then try to correlate this "cloud" of reference points, which represents the bone surface in the surgical site, to the bone surface, which is calculated from the previously acquired CT data. The mathematical process behind it is similar to the least squares distance minimization used in paired point matching. The advantage is, that the surgeon doesn't have to concentrate on finding the specific points, instead he arbitrarily chooses any point on the surface. Because the calculation is based on a lot more points, theoretically the accuracy is improved.

Like in paired point matching, the registration needs a wide opening of the bony structures. This is in contrast to the goal of minimal invasive approaches. Recently, a surface registration technique, which uses an ultrasound probe instead of a digitized stylus, was described (7). This method would allow the combination of minimally invasive approaches and surface matching. The accuracy in a sacroiliac screw placement model was the same as in conventional surface matching, but the average duration of registration was doubled.

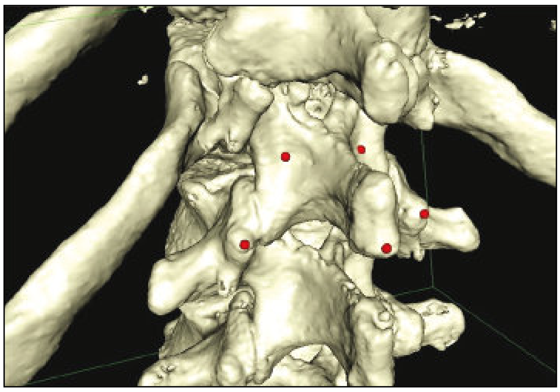

Figure 3: Paired point matching: Some characteristic landmarks (red dots) have to be selected prior to the registration process.

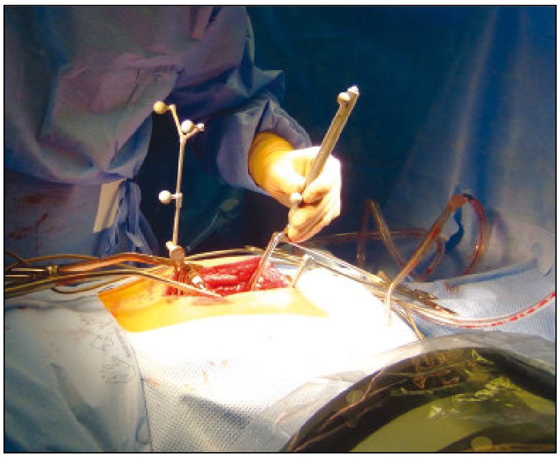

Figure 4: The selected landmarks will be identified intraoperatively and digitized with a digited stylus.

Region matching

The "region matching" technique is a further development from the paired point and surface matching technique. To enhance the accuracy, it uses a library of average bone morphologies. These bone morphologies are then, in a complex mathematical procedure, transformed into a 3D deformable shape, which can enhance and simplify the matching process.

The benefit for the user is, beside the increased accuracy, a slightly easier and safer registration process. After manually defining the bone, which is to be registered and manual fitting of the statistical deformable bone model to the individual CT images, some predefined regions (instead of single checkpoints in paired-point matching) have to be re-identified in the surgical situs. A standard surface matching may follow the region matching procedure, to further enhance accuracy.

The application of the region matching is limited to those structures, which are included in the bone morphology library of the navigation system's database.

CT – Fluoro matching

CT-fluoro matching is an interesting technology, because it enables the use of high-definition CT image quality with a quick and minimally invasive reference process by referencing the CT images to several intraoperative fluoro shots with an optically tracked image intensifier. The major disadvantages of this technique are the high dependency on the quality of the fluoro images and the time shifting problem. Fluoroscope image quality varies a lot and is highly influenced by

Figure 5: Region matching. Predefined regions have to be registered, so the deformable model of the vertebral bone can be fitted to the individual patient's anatomy.

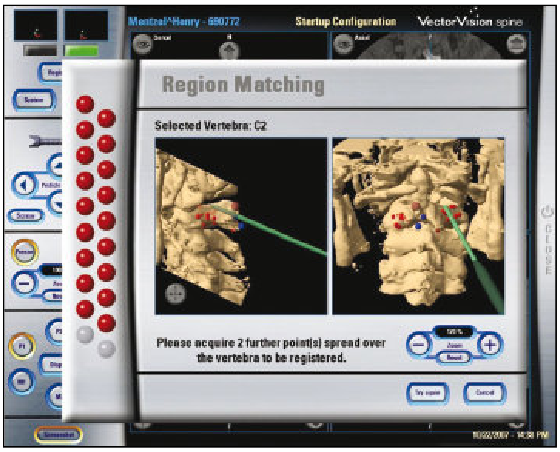

Figure 6: A second step includes a standard surface matching to improve accuracy.

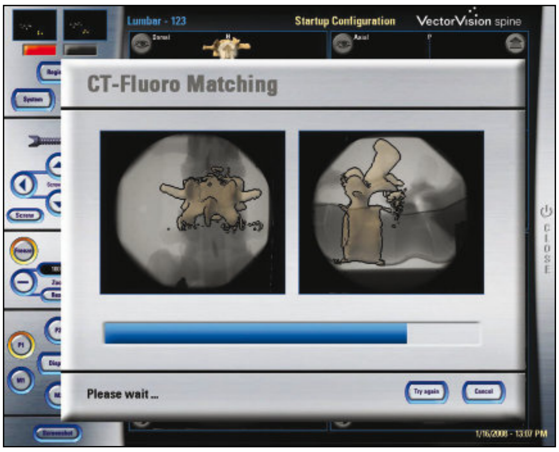

Figure 7: After acquiring 2D-images with a tracked image intensifier, the images are coarsely matched by the surgeon.

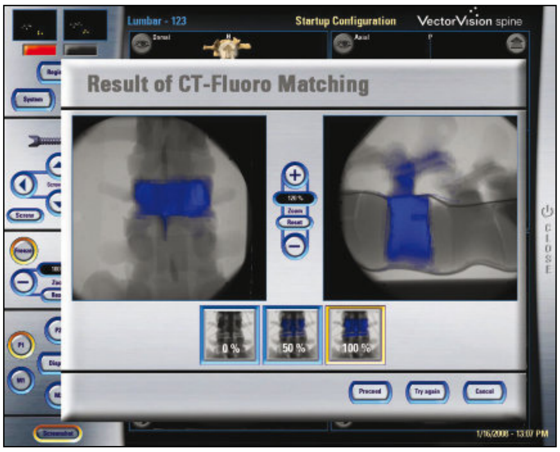

Figure 8: The definitive matching of 2D fluoro and 3D CT images is performed by the navigation system using sophisticated mathematical algorithms.

e.g. bowel gases or superimpositions. Additionally, between CT image acquisition and fluoro shots, the anatomical situation might have changed, which may cause trouble when matching the two image modalities with each other.

Practically, this method will be performed as follows: After at least 2 fluoro shots in ap and lateral with the reference base mounted, a virtual CT-image based model of the vertebra is manually pre-matched to the fluoro images. After this prematching procedure, the navigation system tries to optimize this matching using characteristic landmarks of the vertebral body, for example the pedicles or the transverse or spinous processes.

> CT fluoro matching combines intraoperative imaging with an easy accessible device and high resolution image quality of the CT. The result might be erroneous, if fluoro image quality is poor or anatomical changes have occurred after CT imaging.

Integrated CT / MRI

With the progress of information technology, many companies now offer so called "integrated" OR solutions, which may include an intraoperative CT imaging device. This intraoperative CT is equipped with some markers, so it can be localized in the navigation system's coordinate system during imaging. This enables the immediate registration of the images' coordinate system with the navigation system's coordinate system. There is no time-consuming "paired-point" or "surface-matching" anymore, as in preoperative CT acquisition.

On the first view, this seems to be the ideal solution, because this technique promises to overcome the problem of time shifting between CT acquisition and surgery with its possible morphologic changes as well as the problem of poor image quality and limited field of view of the current intraoperative imaging modalities like 2D- and 3D-fluoroscopy.

The drawbacks are the enormous investment effort and its immobility. Because the devices are mounted permanently to one operating room, it requires a thorough scheduling of any navigated procedures. This might cause some trouble, if different subspecialties are willing to use this technology, because the different OR schedules have to be synchronized. The mobile solutions with "canned" CT or fluoro based matching offers more flexibility in this regard.

Integrated CT/MRI represents today's high end in navigation technology. As in every high-end technology, it is linked to enormous investment efforts.

Fluoroscope based registration

The fluoroscope itself was a major breakthrough in orthopedic surgery, because it allowed for the first time the possibility to extend the surgeon's view beyond the surface of the anatomical situs intraoperatively. After mounting a reference frame, which is equipped with a collimator matrix and a couple of marker points for optical tracking, the fluoroscope can also be used to acquire images for surgical navigation. After its introduction in 1999, 2D-fluoroscope registration for the first time offered the possibility to acquire intraoperative images without the need of an additional registration process and therefore allows minimal access surgery as well as an adaptation to reduction or reposition maneuvers (8). When minimally invasive methods are considered, it is to be remembered, that the mounting of the reference base will need a small, but additional approach as well.

Figure 9: intraoperative CT with an integrated navigation solution offers superior image quality combined with the advantages of intraoperative imaging – at superior cost. (Image: BrainLAB AG, Feldkirchen, Germany)

2D-Fluoro registration

2D fluoro matching is the simplest and quickest method of image based registration. After mounting the reference base, a number of fluoro shots in different projections will be made. The navigation system will then display the position of the navigated instruments in each projection at the same time - without the need of further radiation.

There are many reasons why this method is rarely used any more.

First, you still rely on 2D-projections with summation effects. The image quality is sometimes poor, especially in obese patients or in presence of intestine gases. There's no additional image information, like for instance, transverse slices. Further, a possible dislocation of the reference base after matching, which is the fear of every navigator, is not as obvious as in any 3D (fluoro and /or CT based) matching procedure.

We think, that the main application for 2D-fluoro matching is in those procedures, where you have to switch between different 2D-projections quickly and repeatedly and where a transverse projection is of little advantage. This applies for example for locking screw insertion in intraosseous nailing or sacroiliac screw placement.

2D-Fluoro registration is quick and enables intraoperative imaging without a separate surface matching procedure. Minimally invasive surgery is possible. It provides only 2D images of changing quality and adds no information about the transverse plane.

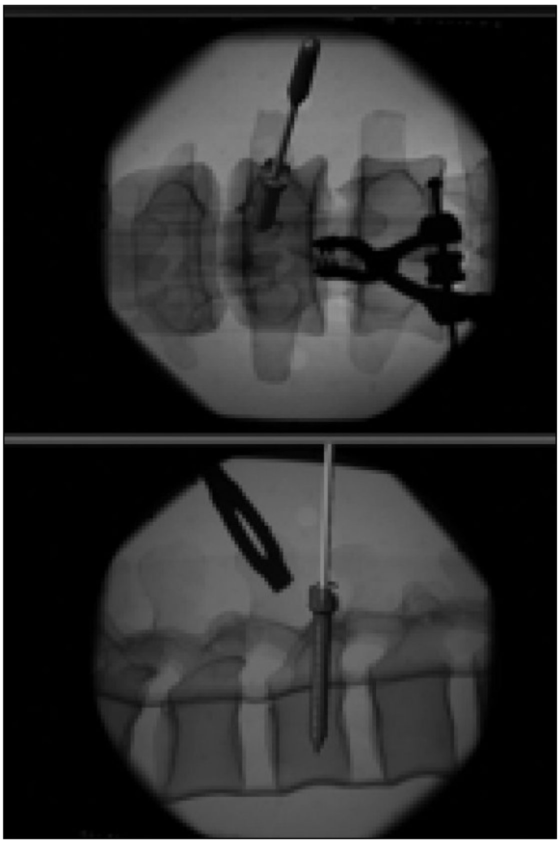

Figure 10: In 2D-fluoro-registration, the surgical instruments are displayed on standard fluoro images in different projections at the same time.

3D-Fluoroscopy

The combination of 3D-fluoroscopy and navigation was intentioned from the early stage of 3D-fluoroscopy development in the 90's. Since that time, the number of reported clinical applications is growing and growing. There are several advantages compared to usual CT-based procedures. Image acquisition takes place when the reference base is already mounted. Further, the C-Arm is registered by the navigation system as well. This is similar to the 2D-C-Arm matching procedure: There's no need for a time-consuming and error-containing manual matching procedure like the surface matching in CT-based matching. The other main advantage is the image acquisition with the patient positioned for surgery. This is important especially in unstable situations, where the relationship between vertebrae or bone fragments may change from supine to prone position or after a reposition maneuver. This often will cause problems in CT-matching, because CT scans are usually performed in supine position, whereas e.g. posterior spine approaches obviously are performed in a prone position. The main advantage compared to 2D-fluoro matching is the third, transverse plane, which is calculated from the three-dimensional image dataset. This adds very useful information, which is crucial in applications like pedicle screw insertion, where the most important structure, the medial wall of the pedicle, is preferably judged in the transverse plane.

The ability to obtain images that represent the current anatomy, is directly and naturally linked to some disadvantages. Compared to CT-based registration, the image quality is poor. Because of the technical limitations due to their mobility, recent 3D-fluoroscopes do not use the high level scanning technology or the sophisticated algorithms for artefact reduction and image enhancement, that are utilized by modern spiral-CT scanners. In orthopedic surgery, soft tissue differentiation is rarely necessary. 3D-fluoro image quality is often good enough to recognize important bony landmarks, like the medial pedicle wall or a joint surface. But by adding some artefacts, for instance from dental prostheses during surgery in the upper cervical spine, or retractors or previously placed implants left in situ, the images might become unreadable. A dilemma that we faced during some operations on the cervical spine is the need to leave artefact-producing retractors in situ during scanning, because there's hardly a chance to remove them and re-insert them afterwards without altering the reference base. Another major source of artefacts, that is difficult to be eliminated, is the reference base itself, which is to be mounted right onto the bony structure of interest.

Beside the image quality, another disadvantage is the scanning volume of the 3D-fluoroscope. Current multislice spiral CT scanners are able to scan a large volume within a few seconds, whereas a 3D-fluoroscan takes up to a minute. Since the scanning process is comparably slow, it is necessary to keep the patient apnoeic for the duration of the scan (e.g. in the thoracic spine). This may be harmful in severely ill patients, like polytraumatized patients. This is especially remarkable, because the maximum scanning volume of the most 3D-fluoroscopes is a cube of about 12cm x12cm x12cm (=1728 cm3) and the instrumentation of multiple segments of an injured spine may necessitate several scans.

Another issue is the scanning process from a logistic point of view. During the scan, the fluoroscope will rotate on a 190° sector around the region of interest. To stay conform to common hygienic rules, the surgical situs is recommended to be wrapped to create a sterile tunnel for the C-Arm. The process of covering the surgical situs is time consuming and costs a lot of draping sheets, especially in large volumes like the spine or the pelvis. Furthermore, it is necessary to avoid any mechanical contact between the fluoroscope c-arm and the patient during the 190° rotation, which might be a problem even in just slightly obese patients. This should definitely be checked for before draping the patient at the beginning of the operation.

> 3D-Fluoro registration delivers 3D images with transverse plane information. The intraoperative imaging with no further need for a separate matching procedure enables minimally invasive procedures and displays the up-to-date morphology of the region of interest. Compared to CT-imaging, it has an inferior image quality and the scanning volume of about 1728 cm3 is smaller.

Image free techniques

The other important group of registration techniques are the image free technologies. "Image free" means, that there's no need to obtain ANY images of the surgical object prior or during the operation. Since many of these image-free techniques mainly rely on estimating the axes of bones and joints instead of capturing the morphology, it is of advantage in those procedures where the emphasis is on a proper mechanical result. In terms of accuracy for total hip arthroplasty, it could be shown that there is no difference between image based and image free navigation (9). For these reasons, image free navigation systems are marching forward in total hip or knee arthroplasty or tibial osteotomies as well as ACL repair (10).

After mounting the dynamic reference bases, the registration procedure itself consists of a combination of some joint motion, like pivoting the hip joint, and percutaneous digitization of some characteristic landmarks like, for instance, the medial and lateral malleolus or the borders of the tibial plateau. These landmarks correlate to specific joint axes, so the navigation system can calculate joint axes as well as mechanical bone axes.

The registration process is easy to perform and really fast. The limitations are seen in very stiff joints or obese patients. If the joint, which is to be registered by joint kinematics (the pivot motion, e.g.) is too stiff, the number of data is too small to achieve a valid result. In obese patients, the thick soft tissue layer covering the bone will increase the error of the percutaneously registered checkpoints, which may lead to inaccurate registration results (11). In these two cases, the application of image based systems may be favourable.

The advantages of image free navigation are obvious: Because additional imaging is not necessary, it saves time, cost and radiation dose for both the patient and the surgeon.

Since in most techniques, it is necessary to mount a dynamic reference base on femur and tibia, additional skin incisions and bone drillholes are required which increase the invasiveness slightly compared to a non-navigated technique.

> The major application of image-free navigation systems lies in joint arthroplasty and osteotomies, because they can visualize the mechanical axes in a very intuitive way. It is quick, but still requires additional incisions for the reference bases.

Summary

After having explained all the different registration techniques and having discussed all their advantages and disadvantages, a generally valid recommendation cannot be made. There is no method, which covers all needs of an orthopedic surgeon.

And even after having discussed all the techniques in theory, it is strongly advised to visit at least one or more institutions, which use navigation, to get a better insight into the practical application of the different techniques.

Nowadays most of the problems with tracking and accuracy as well as visualization and handling of the software have been solved. The trend goes to intraoperative imaging and integrated registration techniques. With the further development of minimal invasive surgical techniques, one of our (the surgeons') greatest wishes to the industry would be to introduce a referencing method, which overcomes the bulky and touch-sensitive reference base (12).

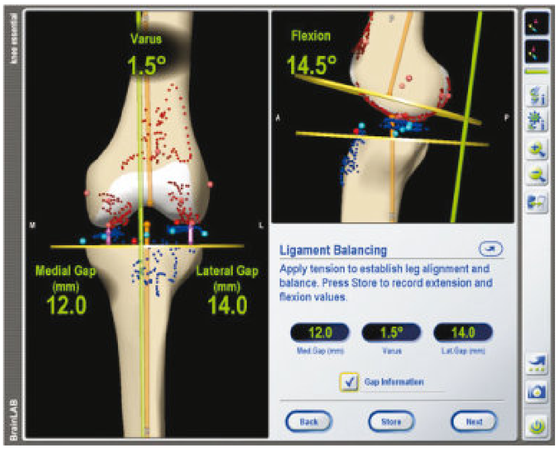

Figure 11: Image free navigation for Total Knee Arthroplasty. The most important mechanical axes are displayed.

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