

A CT-Free Intraoperative Planning and Navigation System for High Tibial Dome Osteotomy

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Abstract

Navigation system improves the accuracy of the surgical procedures. A CT-free intraoperative planning and navigation system, based on SurgiGate system (Praxim-Medivision, La Tronche, France), has been developed for high tibial dome osteotomy. High tibial dome osteotomy is technically demanding procedure with, common complication such as postoperative malalignment or pin penetration of the tibial plateau. This system holds promise to address these problems. Compared to the traditional approach, this system allows the intervention to be performed under navigational guidance with higher precision and safety of the surgical procedure.

1 Introduction

Using image guidance, surgical procedures can be replaced by less invasive alternatives, be planned, and potentially be carried out with higher accuracy. Two types of image guidance can be distinguished. Real-time image guidance by using intraoperative imaging, for example fluoroscopic imaging or ultrasound, has been used for a long time. The advantage of this approach is that surgical tools are displayed live in the patient anatomy, hence providing real-time feedback of the actual situation to the surgeon. And the guidance on preoperatively acquired images. Computer-assisted surgery is an adjunctive surgical process in which the coordinated use of imaging, markers, reference frames, intraoperative sensing and computer workstations allows increased visualization and precise navigation through minimally invasive approaches. CAS planning often involves creation of 3D graphic models of the patients anatomy, which are then linked seamlessly to the surgery through the use of an intra-operative computer workstation. In

surgery, CAS allows identification of the precise contours of the patients anatomical structures, the location of surgical instruments and the positioning of any implants.

Computer-assisted surgery encompasses three key activities: planning, registration and navigation.

Surgical planning is based on imaging. Typically, CAS uses preoperative and/ or intra-operative images taken by CT and/ or fluoroscopy. Different combinations of images can be used, each providing unique benefits to the surgeon.

Registration is the process of establishing a spatial relationship between all locations on the images and the corresponding locations on the actual patient anatomy in the surgical field. A key element of registration is the use of landmarks. Landmarks are locations on the surface of the patient anatomy, which may be reliably identified in both the images and the surgical field. In addition to being readily identifiable, these locations must be rigid with respect to the surrounding anatomy so that their positions never change. Landmarks may be discrete anatomical structures or artificial markers such as implanted pins, called fiducials, which are screwed into the bone. Registration establishes image to actual anatomy relationships, but that is not enough. The spatial relationships must then be maintained throughout the surgery. This is done either by immobilization (Immobilization simply means keeping the anatomy fixated in one place) or by a process called dynamic referencing. Dynamic referencing allows movement while still preserving the relationship. It involves rigidly fixing a reference frame to the surgical anatomy. The purpose of this type of frame is not to immobilize. Rather, it allows infrared, electromagnetic and/ or radio - frequency sensors to detect and measure movement of the patient, for which the computer then compensates. Dynamic referencing is used for example, in knee surgery where movement is needed to determine and test the correct angle for placement of the implant.

Navigation is intra-operative. In essence, this is the tracking of instruments and tools within the surgical field in real-time and displaying this movement overlaid on the images and 3D models of patient anatomy. This feature means that the surgeon does not have to make a large incision to directly see the anatomy and to follow the progress of the procedure.

2 Materials and Methods

2.1 Surgi Gate

CT-free intraoperative planning and navigation system for high tibial dome osteotomy is based on SurgiGATE system (Fig. 1). SurgiGATE enables the surgeon during the operation to continually visualize on the monitor in realtime the location of the surgical instruments in relation to preoperative pictures (e.g. Computerized tomography/CT scans/or fluoroscopy) in the bone operated on. An infrared camera in the operating room monitors the instruments and shows them in relation to the CT/fluoroscopy scan on the monitor. This allows the surgeon to determine the precise position of the tip of his instrument, which is not visible in the operating field.s

2.2 Optoelectronic infrared tracking localizer (OptoTrack3020)

A 3D motion, position and orientation measurement system. It consists of infrared light emitting diode markers. It's a localizer for the real time monitoring of the position and the orientation of the surgical tools and anatomical structures in operating room. The OptoTrack 3020 system measures 3D motion and position by tracking markers attached to a subject. As the subject moves, OptoTrack detects the positions of the markers (infrared light-emitting diodes) and simultaneously calculates precise three dimensional data for each. This 3D data is displayed in real time, allowing you to monitor data throughout the trial.

2.3 Sun ULTRA10 workstation

The workstation communicates with the infrared tracking system through customized software using client/server architecture.

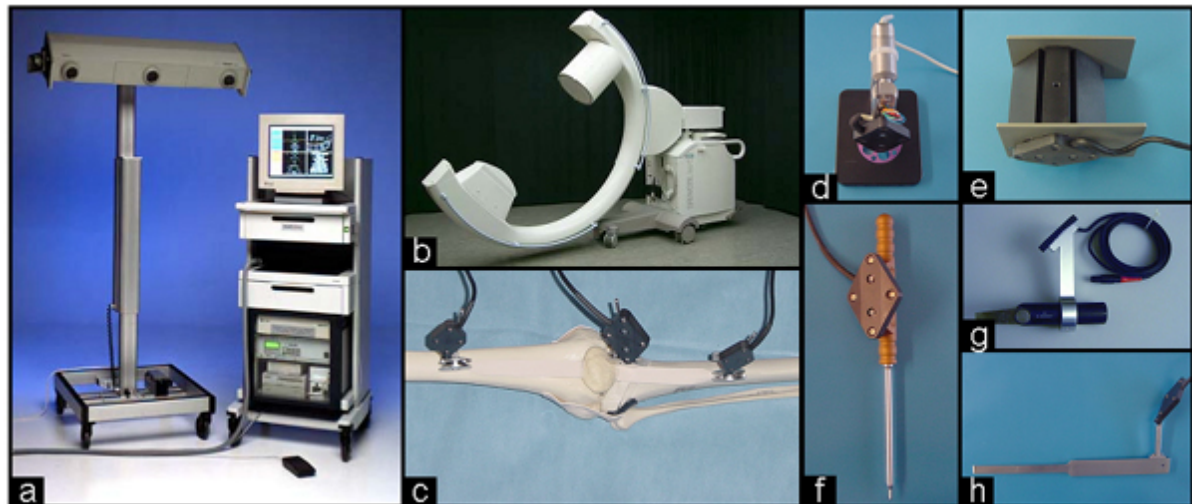


Figure 1: SurgiGate System consists of (a) optoelectronic localizer and computer system, (b) registered fluoroscopic C-arm, (c) dynamical reference bases affixed to the affected limb, and navigated instruments: (d) gravitational direction measurement tool, (e) accuracy checker, (f) pointing device, (g) navigated drill, (h) navigated chisel

2.4 Navigated instruments

The navigated instruments can be divided into 3 groups. The first group consists of calibrated fluoroscopic C-arm, which is used for image acquisition and landmark registration. The next group consists of a navigated drill and chisel. The last group includes three dynamic reference bases (DRB's), which are affixed to the limb.

2.4.1 Calibrated fluoroscopic C-Arm

Intraoperative fluoroscopy is an invaluable tool for the orthopaedic surgeon. It allows the surgeon to visualize patient anatomy in real time and assist in implant insertion. Virtual fluoroscopy technology uses a calibration fixture that attaches to a C-arm. Optoelectronic markers are placed on the C-arm to track its position in space. Fluoroscopy has the advantage of simplicity and increased accuracy without needing a preoperative CT scan. The motivation to use fluoroscopic C-arm for intraoperative bone modelling, spatial location, and registration is that it is immediate, non-invasive, and ubiquitously available. In order for the system to function properly, the following steps are necessary. First, an empty C-arm image of the calibration grid is acquired and transferred to the computer for later calibration. C-arm images of the patient are then transferred into the computer via a standard video or digital link. At the time of image acquisition, the relative position of the patient and the C-arm is measured. During this step, the position-measuring sensor at the head of the bed detects the signal from the LEDs attached to the fluoro unit and the patient. The image is then calibrated to remove distortions and account for magnification. Finally, corrections are applied to compensate for mechanical bending of the C-arm due to the effects of gravity. The calibration allows the computer to build a mathematical description of the images that geometrically relates how a given position relative to the patient projects onto the fluoroscopic image. At the same time, the mathematical description also relates how a given picture element of the C-arm image projects back through the patient to the radiation source via the calibration grid. Finally, the computer measures the position of the surgical instruments via LED emissions on the instruments to the position-measuring sensor. The position of the instrument is then superimposed onto the fluoroscopic images in multiple planes and in real time. The 3-D image is reconstructed from a series of 2-D images taken in different orientations. Fluoroscopy has the advantage of providing real-time movements and changes of the surgical objects as well as the end-effectors. Changes in the anatomy of the patient due to surgical actions can be visualized. However, the C-arm must be carefully calibrated to ensure the accuracy of the acquired images. Two fluoroscopic images of the femur are intra-operatively acquired using an optically tracked c-arm. The surgeon then proceeds to specify features in the 2D images, from which information on their 3D counterparts can be calculated by means of projective geometry. The use of highly advanced virtual fluoroscopy technology helps spine surgeons understand the position of surgical hardware and instruments in relation to critical anatomic structures in the spine. Often, knowing exactly where you are can be the difference between a successful case and one with complications. Also, the proliferation of less invasive procedures presents challenges in planning trajectory paths for drilling, measuring hardware, and locating difficult to find anatomy. Virtual fluoroscopy technology is a solution for addressing these issues. The surgeon takes the necessary images, often AP and lateral. The calibration fixture automatically registers the images to the patients anatomy. Then, during the procedure, the surgeon is able to plan trajectories, locate difficult anatomy, and determine the necessary lengths of screws and other surgical hardware. In addition to improved accuracy, one of the obvious benefits to virtual fluoroscopy is reduced dose for the patient and the surgical team, since the need for continuous fluoroscopy is eliminated. The result is that the surgeon can precisely see his surgical tool moving within a static X-ray view of the patient. Such a calibrated C-arm provides several benefits: (1) The C-arm can be numerically

aligned at exact angles with the tracked patient position without X-ray exposure, (2) there is no longer a need for constant X-ray exposure to guide surgical tool movement within the image, (3) the surgeon can view tool movement on more than one view of the bone at a time to precisely control 3D movements and, (4) Semi-automatic 3-D reconstruction of anatomic landmarks based on two or more C-arm images allows precise intraoperative geometric measurements.

2.4.2 Navigated Drill and Chisel

This navigated instruments are used for cutting the bone.

2.4.3 Dynamic Reference Bases (DRB's)

In order to determine the exact spatial orientation of a patient or any surgical instruments, at least 3 non-collinear points on a fixed body (DRB) must be recognized by a tracking system which then inputs data into the computer for virtual referencing. The camera system generally consists of two or three charged couple devices (CCDs) that pick up the light signal from the DRBs. The computer referencing protocol collects all components, including the patient's anatomy and all registered surgical instruments. The DRBs may be active, consisting of light emitting diodes (LEDs) or passive where reflector balls are placed on the DRB and reflect infrared light originating from a light source on the camera. The computer can then detect the specific DRB such as the marker on the distal femur. For all DRBs the process is simply finding the appropriately defined DRB with the camera system and registering it with the computer. Following exposure, DRBs are attached to the femur, and the proximal and the distal part of the tibia.

3 Osteotomy

High tibial osteotomy is a procedure used to treat knee arthritis by younger adults, for whom total knee replacement is not advised. These knees often have a bowed appearance. The main indications for HTO is pain and angle deformity of the knee. The most common condition treated by high tibial osteotomy is 'unicompartmental osteoarthritis' - where the one half of the knee is damaged by arthritis while the other half is still in good condition. There are two basic osteotomy types for angular deformity correction: 1.angulation-only osteotomies (opening wedge and closing wedge type) 2.angulation with translation osteotomies (straight cut or circular cut(dome)) The best treatment option depends on clinical relevancies such as severity and location of the deformity, joint line oblique angle, leg length discrepancy, soft tissue coverage, and so on. HTO is generally recognized as a technically demanding procedure with a long learning curve. Failures may occur even in operations by experienced surgeons. The most common complications include postoperative malalignment and inaccurate bone cutting. These problems can be addressed by using computer assisted surgery.

3.1 CT-based intraoperative guidance system and robot assisted system for closing wedge osteotomy

In the closing wedge osteotomy, a cut is made in the lateral(sideways) side of the knee to allow the surgeon to see the upper end of the tibia. Once the tibia bone is exposed, two cuts are made through the upper tibia in the shape of a wedge. The surgeon takes out the wedge, and the two sides of the tibia are brought closer together and held in position with a metal plate or pins. This changes the angle of the tibia and helps straighten the alignment of the knee. After fixing the two edges of bone with a plate or pins, the surgeon stitches the skin together, and the leg is placed in a padded splint to protect the knee joint. Unlike the opening wedge osteotomy, the closing wedge osteotomy requires removal of bone to allow angular correction. There is full bone-to bone contact at the end of correction. The final length of the bone is shorter than in the opening wedge type. CT-based intraoperative guidance system and robot assisted system have been developed for closing wedge osteotomy. The advantage of the CT-based system is the accurate removal a wedge from the bone and providing detailed 3D images. However CT-scan exposes the patient to a considerable amount of radiation, and errors in registration pose a possible pitfall for the operation and the potential risk of infection caused by implanted fiducials markers. When extreme precision is required, the registration can be based on external fiducial markers implanted on the patient.

3.2 CT-free hybrid computer assisted navigation system for opening wedge osteotomy

In the opening wedge osteotomy, a cut is made in the medial side of the knee. Care is to protect the nerves and blood vessels that travel across the knee joint. Once the tibia bone is exposed, one cut is made through the upper tibia. A fluoroscope or X-rays are used to make sure the cut is in the right place. After the bone is cut, the two sides of the tibia are separated to form a wedge-shaped opening. This opening is then filled with bone graft. The bone graft is usually taken from pelvis bone, through a cut in the side of your hip. The bone graft is held in position with a metal plate or pins. After fixing the two edges of bone with a plate or pins, the surgeon stitches the skin together, and the leg is placed in a padded splint to protect the knee joint. With opening wedge osteotomy, as with closing wedge osteotomy, the appropriate center of rotation of angulation must be identified and marked. The osteotomy is simpler because it is a straight cut. Opening wedge osteotomy is associated with the risk of bone healing problems, because of the limited bone contact. Opening wedge correction can be performed actually or gradually, depending on the hardware used and the severity of the deformity. The larger the deformity is, the more stretch will result from an acute correction. Opening wedge correction stretches the soft tissue more than does closing wedge correction. CT-free hybrid computer-assisted navigation system for opening wedge osteotomy provides reliable solution with using fluoroscopic images instead of ct-scan.

3.3 CT-free planning and navigation system for high tibial dome osteotomy

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3.3.1 Osteotomy planning

The planning procedure consists in general of the following steps: images acquisition, determination of the desired osteotomy pose and planning the implant position. An effective intraoperative osteotomy planning is based on fluoroscopic images taken during the procedure, which allows the surgeon to interactively determine the osteotomy parameters, such as the severity of the deformity, type of the fixation and bone quality, and perform the intervention with the help of a navigation system. Besides the fluoroscopic images, no other imaging is needed. The other following parameters must be known to successfully perform the intervention such as the position of central rotational axis, the radius of the osteotomy and the distance between pinholes. This parameters are done with the help of the knee AP images(Fig.2). With the help of knee lateral images(Fig.3), the surgeon determines the posterior slope of the osteotomy plane. These fluoroscopic images of the knee are intraoperatively acquired using an optically tracked C-arm. Our planning system determines these values, based on fluoroscopic images and the parameters describing the desired osteotomy. The planning system permits the surgeon to determine the exact location of drill holes. The intervention is then performed with the help of a navigation system and tracked instruments.

3.3.2 Landmark Registration

The fluoroscopic images of the knee and hip are intraoperatively acquired and uploaded into navigation system at the beginning of operation. Preceding the image acquisition and the DRB's

are attached to the femur and the tibia of the affected limb. The images must be taken in AP (anterior/posterior) and in lateral view. Landmark based registration can be applied to any image. In image-based registration, anatomical landmarks are extracted from the images, and their spatial locations are computed from the camera pose and internal parameters. We use an intraoperative imaging device a mobile fluoroscopic C-arm. The advantage of image based registration is that it does not require contact or additional surgical exposure and uses readily available intraoperative imaging devices. Many points can be extracted accurately and automatically with advanced image processing techniques. However, this technique depends on many more factors, such as the geometric characteristic of the imaging camera and its pose, the image quality, and the quality of feature localization in the images. Image-based landmark registration consists of matching a set of 3D points with a set of 2D points extracted from the images. Image based registration can be divided into extrinsic, i.e., based on foreign objects introduced into the imaged space, and intrinsic methods, i.e., based on the image information as generated by the patient. Extrinsic methods rely on artificial objects attached to the patient, objects which are designed to be well visible and accurately detectable in all of the pertinent modalities. The main drawbacks of extrinsic registration are the prospective character, i.e., provisions must be made in the pre-acquisition phase, and the often invasive character of the marker objects. Intrinsic methods rely on patient generated image content only. Registration can be based on a limited set of identified salient points (landmarks), on the alignment of segmented binary structures (segmentation based), most commonly object surfaces, or directly onto measures computed from the image grey values. Landmarks can be anatomical, i.e., salient and accurately locatable points of the morphology of the visible anatomy, usually identified interactively by the user

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3.3.3 Navigation

The planned osteotomy and wedge removal are performed with navigated instruments. The surgeon has also the option to make individual modifications of the treatment plan, including the size, position, and orientation of the implant. Surgical instruments are continuously tracked

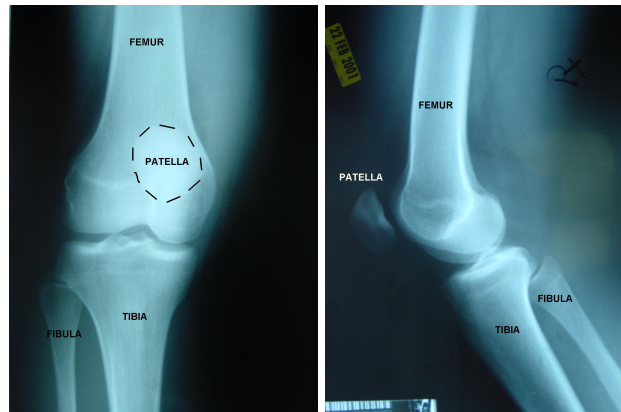


Figure 2: Fluoroscopic images: knee AP (left), knee lateral (right) used for osteotomy planning, landmark registration and osteotomy navigation

by the navigation system to judge the precise position and alignment of the planned bone cuts. This provides the surgeon with comprehensive real-time information, which allows him to make confident decisions for greater control over the surgical outcomes. It is also possible to verify and optimize intra-operatively bone resections (cut verification). Margins of errors can be discovered and corrected during the surgery. Additionally to that kinematic evaluation software provides absolute values on varus/valgus, joint gap sizes and flexion and extension positions, enabling the surgeon to achieve an optimally balanced leg alignment. The navigation system can help to immediately judge the accuracy of the achieved result by inverse calculation of the osteotomy parameters.

Bone cutting One of the most required result is the accuracy of the procedure. All drill holes should be parallel in both the frontal and sagittal planes, and each bone cut with osteotom should also follow the same direction. An inappropriate drill or bone cut may cause problems, such as pin penetration of the tibial plateau or damage to the tibial neurovascular structures. With the use of navigation system, we can address this technical problems. The integration of a conventional X-ray intensifier into the navigation system makes it possible to use the fluoroscopy as a data-supplier for real-time navigation of surgical instruments. The procedure is based on the virtual connection of the fluoroscopic images and the position of the navigated instruments used for bone cutting such as calibrated drill and chisel. For this purpose it is necessary to attach markers to the surgical instruments and to the patient. With virtual fluoroscopic technique, the surgeon is able to monitor the position and orientation of the surgical instruments. The surgeon can minimize the risk of intraoperative technical pitfalls and achieve a safe and accurate osteotomy.

Deformity correction Is the most difficult step. The alignment is achieved and the internal fixation implant is in place. The navigation system showed a high possibility in the instrument visualization and implant location such all relevant clinical parameters. The navigation guidance enables the surgeon to perform deformity correction accurately.

4 Conclusion

High tibial osteotomy is a widely accepted treatment of medial compartment osteoarthritis as well as other lower extremity deformities. However, it is a technically demanding procedure. The lack of exact intraoperative real time control of the mechanical axis often results in post-operative malalignments, which is one reason for poor long term results. These problems can be addressed with the use of a surgical navigation system. Following exposure, dynamic reference bases (DRBs) are attached to the femur, and the proximal and the distal part of the tibia. After intraoperative measurement of the deformities and correction planning, the osteotomy is performed under navigational guidance. The wedge size, joint line orientation, and tibial plateau slope are monitored during correction.

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