ABSTRACT
Proximal femoral osteotomy is a commonly accepted but technically demanding surgical procedure. Despite the recent developments in preoperative planning and simulation, it remains difficult in the clinical practice to translate the planned procedure to patient due to the lack of reliable intraoperative tools for verifying operative wedge size and functional parameters. A surgical navigational guidance system is therefore developed based on virtual fluoroscopic techniques aiming to provide surgeons with a novel intraoperative tool enabling the precise implementation of planned surgical procedures and minimization of the risk of intraoperative complications.

KEY WORDS
Computer-aided surgery, fluoroscopy, osteotomy, and navigational guidance

1. Introduction

Despite recent advances in hip arthroplasty, there are still numerous indications for joint saving procedure, particularly in young and active patients. Of special importance in this context is proximal femoral osteotomy that aims to change the position of the femur head in relation to the femoral shaft and thus to place the stress on healthy areas of the hip joint [1-6]. To accomplish this, the femur is normally cut through intertrochanterically and a wedge is excised. The proximal and distal fragments are then tilted and/or rotated against each other until the desired target position is achieved (Fig. 1).

Osteotomies need to be performed accurately in order to achieve an increased weight-bearing surface and a decreased joint force [4]. They are, however, technically demanding due to (1) the complexity of the three-dimensional (3D) deformity at the hip joint and thus the problems in preoperative planning, and (2) the difficulties of the exact operative realization of the planned procedures during actual surgery.

Computer-aided techniques have been introduced in order to address these problems. As the major contributions in this field, various preoperative planning [7-9] and simulation [8-9] softwares have been developed, which allow accurate analysis of the 3D deformity, interactive simulation of different osteotomy techniques, and thus optimal planning of the surgical procedure. One of these is BoneArchitector [9], with which the stack of DICOM images (CT or MRI) is segmented and a volumetric 3D model is generated. With tools for editing 3D scenes, virtual osteotomies can be performed and optimal procedure can be planned.

In contrast to these developments, little has been done to address the second issue. It remains very difficult in the clinical practice of surgery to translate the optimization achieved in the planning phase, even when it is accurate, to patient due to the lack of reliable intraoperative tools for verifying operative wedge size and functional parameters [6]. With conventional “free-hand” surgical techniques, the success of an operation is largely depends on surgeons’ expertise, which makes clinical outcomes unpredictable. A computer-aided navigation system is therefore proposed in this paper aiming to provide surgeons with a novel intraoperative tool enabling the precise implementation of the planned surgical procedure and minimization of the risk of intraoperative complications. The implementation and laboratory evaluations of the system will be described in detail.

2. Materials and Methods
The preoperative planning and simulation is obviously essential and is the prerequisite of a subsequent successful
procedure. However, it is beyond the scope of this paper. For using the proposed system, the surgeon preoperatively determines the osteotomy position and amount of angular correction and transfers them to the navigation system before operation. The actual procedure is then performed in the following steps: (1) affixation of dynamic reference bases (DRBs) at the femur and tibia, and acquisition of fluoroscopic images with a registered fluoroscopic C-arm, (2) digitization of anatomical landmarks and measurement of functional parameters, (3) planning of osteotomy plane with the aid of fluoroscopic images, and (4) navigational guidance for bone cutting and deformity reduction. A third DRB is fixed proximally at the femur before bone cutting for measuring the movement between the proximal and distal bone fragments.

2.1 System Overview

Fluoroscopy-based navigation system has been described previously [10-11] and used successfully in many applications such as total hip arthroplasty [12] and high tibial osteotomy [13]. The system presented here follows a similar methodology.

As shown in Fig. 2, an optoelectronic infrared tracking localizer (OptoTrack 3020, Northern Digital Inc., Canada), mounted on a movable stand, is used to track positions of optical targets equipped with infrared light-emitting diodes. These targets are attached to anatomical bodies, to the image intensifier of the fluoroscopic C-arm, and to other relevant surgical instruments such as the saw and chisel. A Sun ULTRA 10 workstation (Sun Microsystems Inc., Mountain View, Canada) was chosen for image processing and visualization task. It is connected to the video output of the C-arm for the acquisition of fluoroscopic images. The workstation communicates with the infrared tracking system through customized software using client/server architecture.

![Fig. 2. The schematic view of the navigation system.](image)

2.2 Anatomical Landmarks

Following the fixation of DRBs at the femur and the tibia, fluoroscopic images are acquired and uploaded to the navigation system including anterior-posterior (AP) and lateral images of the knee, AP and ¼ of the hip, and optionally AP and lateral of the ankle.

Based on these images, anatomical landmarks situated at the hip, knee, and ankle joint are digitized sequentially with a previously introduced biplanar image-based 3D point reconstruction algorithm (Fig. 3) [12]. This approach allows the digitization of deep-seated bony anatomical features that are not accessible by a pointing device without additional soft-tissue damage. With these surgeon-defined landmarks, the femoral neck axis, femoral shaft axis, femoral mechanical axis, tibial mechanical axis, and the mechanical axis of the affected limb can be defined. A patient-specific skeleton model and a reference coordinate system are then established accordingly (Fig. 4).

![Fig. 3A-B. (A) The screenshot and (B) schematic view of fluoroscopy-based landmark digitization. As shown in the figure, a landmark is manually identified in two different fluoroscopic images (V1 and V2) before a computed back-projection determines the associated X-ray beams. The closed intersection point of these X-ray beams leads to the 3D landmark V.](image)

2.3 Functional Parameters

Morphological abnormality and functional parameters are then measured intraoperatively. As shown in Fig. 5, the femoral shaft neck angle (cervico-diaphysaire, CCD) is defined as the subtended angle between the femoral neck and shaft axes on the frontal plane, and the anteversion [14] is defined as the intersectional angle between femoral neck axis and femoral posterior condylar axis on the
transversal plane. The femoral length is defined as the distance between the hip and knee centers, and the offset from the hip center to the shaft axis is determined as the perpendicular distance between the hip center and femoral shaft axis. In addition, after the surgeon defines the “neutral” position between the pelvis and leg, the range of motion of the hip joint can be measured.

Despite the fact that the osteotomy is performed at the proximal part of the femur, it is important to measure the axial alignments of the affected limb including varus/valgus and flexion/extension angles. This is because the realignment of the hip joint often associates with the alteration of the biomechanics of the knee. Therefore, it is necessary to monitor them and to maintain the straight line of the lower limb after the operation [3], [5].

2.4 Intraoperative Planning

Based on the intraoperatively determined patient’s anatomy, the osteotomy is planned with the aid of fluoroscopic images. From the mathematical point of view, a frontal planar closing wedge osteotomy consists of two cutting planes and a lateral or medial hinge axis. The associated sagittal flexion or extension osteotomy can be added by tilting one cutting plane anteriorly or posteriorly. In such a case, the hinge axis becomes a rotational point.

The planned cutting planes are, based on the preoperative planning data, transparently superimposed on fluoroscopic images with key features highlighted as shown in Fig. 6. The surgeon can then simply follows the preoperative planning or make necessary modifications according to intraoperative clinical findings.

2.5 Navigational Guidance

The planned osteotomy and wedge removal are performed with a calibrated chisel and saw based on the positional information given by the navigation system. As can be seen from Fig. 7, the applied instrument is projected on fluoroscopic images for the continuous visualization of the progress of bone cuts. In addition, the deviation between the instrument and the planned cutting plane is calculated and displayed in real time, which enables the precise adjustment of the position and orientation of the instrument.
The deformity correction is then performed following osteotomy. This is the most crucial, also the most difficult step with conventional techniques due to the lack of reliable tools for verifying operative wedge size and functional parameters. However, navigational guidance makes it much easier. During the process of deformity reduction, the surgical relevant parameters are continuously calculated as shown in Fig. 8, which provides surgeons with a comprehensive view of the clinical outcome and thus enables them to accurately implement the planned surgical procedure and to minimize the risk of intraoperative complications such as residual deformity, trochanteric angulation, or leg length discrepancy.

3. Validation Study

Two in-vitro phantom studies were performed to validate the system.

3.1 Functional Parameters

Fluoroscopic images inherently carry complexity caused by the overlay of anatomical structures and the incorrect positions of the patient or misalignment of the C-arm during image acquisition, which make the projectional representation of 3D anatomy difficult to interpret and thus may introduce registration errors. To assess such potential errors, 9 fluoroscopic images, including one well-aligned and 8 misaligned images, were acquired as shown in Fig. 9 with a normal plastic bone model (Synbone AG, Davos, Switzerland) along hip AP, hip lateral, knee AP, and knee lateral directions, respectively. The landmarks were then reconstructed with these images, which resulted in 9×9 values for each landmark. The reproducibility of functional parameters was defined as the consistency of values calculated with these digitized landmark positions accordingly.

With 15° deviation of the C-arm when acquiring the images, the maximum deviation from the mean value of the femoral neck shaft angle, anteversion, femoral length, and hip center to shaft offset were found to be 7°, 6°, 1 mm, and 3 mm, with a standard deviation (95% confident interval) of 4.4°, 4.6°, 1.4 mm, and 3.2 mm, respectively.

In addition, a CT-scan was acquired with a slice thickness of 1.25 mm on the plastic bone phantom after implanting fiducial markers. The positions of landmarks are then directly extracted from the 3D volumetric data as shown in Fig. 10. These data were rigidly registered to the patient specific coordinate system using a simple paired-points matching algorithm and then served as the “gold-standard” position of the anatomical landmarks. The accuracy of the functional parameters was defined as the discrepancy between the values reconstructed from the

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**Fig. 7.** The osteotomy is performed under navigational guidance with the applied instrument and the planned cutting plane superimposed on fluoroscopic images. The deviation of the instrument is displayed at the top of the window using a virtual cutting slot.

**Fig. 8.** The deformity is corrected under navigation guidance with the real-time feedbacks including the axial alignment, the femoral morphological parameters, the 3D wedge size and its components, and the intersection point of the weight-bearing axis at the tibial plateau coordinate system.

**Fig. 9.** Experimental set-up for the acquisition of fluoroscopic images.
fluoroscopic images and the “gold-standard” values calculated from the data directly extracted from the CT volume. It was found that the error of mean was 3.5°, 2.0°, 2 mm and 2.5 mm for the femoral neck shaft angle, anteversion, femoral leg length, and hip center to shaft offset, respectively.

Fig. 10. A CT-scan was taken on the plastic bone phantom and the positions of anatomical landmarks were directly extracted from the 3D volumetric data.

3.2 Deformity Correction

Proximal femoral osteotomy involves not only rotations but also translations between two bone fragments. To simulate such a 3D complex surgical procedure, a test bench was designed and implemented that consisted of 6 dimensions of freedom (DOF). A plastic bone model was cut and fixed on it as shown in Fig. 11. By this way, a varus/valgus, extension/flexion, or rotational osteotomies could be simulated. The actual movement between the two bone fragments were measured using attached goniometers and rulers with a resolution of 1 mm and 1° respectively.

Fig. 11. The test bench used for the simulation of osteotomies. Six DOFs of rotations and translations are indicated with arrows in the figure.

For a typical proximal femoral osteotomy, 10°, 20°, and 30° frontal planar valgus osteotomy with/without an associated 10° sagittal planar extension osteotomy were simulated with the test bench. The rotation and translation between the proximal and distal bone fragments were measured with the test bench as well as determined with the navigation system, and the differences were calculated afterwards. It showed that the average discrepancy was 1.6° with a maximum error of 3°.

4. Discussion and Conclusions

Proximal femoral osteotomy is a technically demanding procedure involving complex multi-planar 3D reorientation and translation of the proximal femur. The success of such procedure depends on (1) the accurate deformity analysis and preoperative planning, and (2) precise implementation of the planned procedure during surgery. Conventional preoperative planning and “free-hand” surgical techniques have so far been inaccurate and tended to make the clinical outcome unpredictable [1-6]. Therefore it is rational to introduce computer-aided techniques in this context. However, despite various recent developments in preoperative planning and simulation, little has been done, except the pilot study reported by Burgkart et al [15], to explore an intraoperative navigational system. To our best knowledge, this paper remains the first intensive investigation regarding this issue.

Different osteotomy techniques have been introduced such as intertrochanteric or subtrochanteric techniques. [1-6] Main differences among them are only indications, degree of reconstruction, and the rate of complications. In general, the proposed navigation system supports all these techniques. Although image free navigation system has demonstrated encouraging results in certain applications such as knee arthroplasty, it may not be applicable for the proximal femoral osteotomy due to the fact that it is very difficult to obtain the necessitated landmarks using image-free approaches. For example, the widely used kinematic pivoting movement may not be valid for the registration of the hip center in patients with predominant anterosuprolateral osteoarthrosis at the hip joint due to the irregular non-spherical pathological shape of the femoral head and thus the invalidity of the assumption of ball-and-socket mechanism. We believe in that the fluoroscopy-based navigation is a better choice for these indications.

One prerequisite for the clinical usage of the proposed system is that the required functional parameters can be determined with sufficient accuracy. Our laboratory evaluation suggested that the fluoroscopy is a reliable means for the determination of anatomical landmarks and therefore the establishment of patient specific coordinate
system and calculation of functional parameters. Because the presented system is an extension of our previous works on high tibial osteotomy [12], only the newly introduced parameters were validated in this paper. Other functional parameters including varus/valgus, extension/flexion angle, and intersection position of the weight-bearing axis at the tibial plateau coordinate system have been validated previously and successfully used in the clinical practice of the surgery [13].

The limitations of the current study are inherently to in-vitro conditions. However, these conditions corresponded to the worst-case scenario for measurements. In the current study, the misalignment of the C-arm was estimated to be 15°, which was actually much worse than the normal clinical situation in our previously acquired experiences. Further more, according to Wright et al., the accuracy in achieving a true AP image at the knee joint can be within 5° if using the patella as a reference [15].

In conclusion, although further clinical evaluations are still necessary, the in-vitro evaluations already showed the encouraging results. Our investigation suggests that the navigational guidance provided by the newly proposed system can improve the accuracy and reproducibility, and consequently improve the clinical outcome of this surgical procedure.

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