Improved Screw Placement for Slipped Capital Femoral Epiphysis (SCFE) Using Robotically-Assisted Drill Guidance

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Abstract. Slipped Capital Femoral Epiphysis (SCFE) is a common hip displacement condition in adolescents. In the standard treatment, the surgeon uses intra-operative fluoroscopic imaging to plan the screw placement and the drill trajectory. The accuracy, duration, and efficacy of this procedure are highly dependent on surgeon skill. Longer procedure times result in higher radiation dose, to both patient and surgeon. A robotic system to guide the drill trajectory might help to reduce screw placement errors and procedure time by reducing the number of passes and confirmatory fluoroscopic images needed to verify accurate positioning of the drill guide along a planned trajectory. Therefore, with the long-term goals of improving screw placement accuracy, reducing procedure time and intra-operative radiation dose, our group is developing an image-guided robotic surgical system to assist a surgeon with pre-operative path planning and intra-operative drill guide placement.

Keywords: Slipped Capital Femoral Epiphysis (SCFE), Robotically-assisted orthopedic surgery, Computer-aided intervention.

1 Introduction

Slipped capital femoral epiphysis (SCFE) is a common hip disorder in early adolescence that results in displacement of the proximal femoral epiphysis into a posterior and inferior position in relation to the proximal femoral metaphysis. Symptoms of SCFE include groin or knee pain, decreased hip range of motion, and a limp. Due to the risk of permanent injury to the hip joint with continued displacement, SCFE is considered an orthopedic emergency. Surgical treatment is aimed at stabilization of the proximal femoral epiphysis to prevent further displacement, and traditionally has been done by placing one or two screws from the proximal femoral metaphysis across

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the physis into the femoral head (shown in fig. 1). The SCFE procedure is done in a minimally invasive manner using X-ray fluoroscopic imaging for visualization. Minimally invasive surgical techniques are advantageous to patients, as they are less disruptive to the soft tissues and often lead to faster functional patient recovery. Despite this benefit, the lack of direct field visualization while operating, as opposed to open surgery, makes these techniques much more technically challenging and requires the surgeon to have an extensive three-dimensional understanding of anatomy to perform the procedure safely. Minimally invasive techniques in orthopedic surgery are often aided by X-ray fluoroscopic imaging. However, concerns exist regarding radiation dose when using fluoroscopy, particularly in pediatrics.

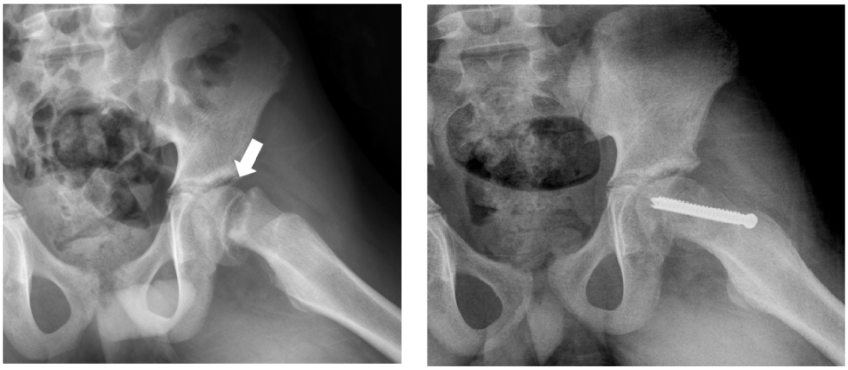

Fig. 1. (Left) Presenting radiograph of a child with slipped capital femoral epiphysis. The proximal epiphysis is displaced posteriorly on the femoral neck (arrow). (Right) Hip radiograph showing fixation of the slipped capital femoral epiphysis with a single screw into the hip.

In the current treatment of SCFE, the surgeon uses intra-operative fluoroscopic imaging to guide the placement of the screw guide pin, confirm the drill trajectory, and direct the final screw placement. Optimal placement of the screw requires precision, with the best position being perpendicular to the physis and deep and central in the femoral head. Improper screw placement, either off center or poorly angled in relation to the physis, leads to the possibility of significant complications from the implant including hip joint penetration, chondrolysis, femoral head vascular injury, proximal femoral avascular necrosis, and poor patient outcomes. The accuracy, duration, and efficacy of this procedure are dependent on surgeon skill and experience. Longer procedures involve higher radiation dose, to both the patient and surgeon.

Other researchers have investigated navigation techniques for orthopedic procedures. For distal locking of intramedullary implants, Suhm et al. showed that radiation exposure time could be decreased from 108 seconds to 7 seconds by using a computer aided surgery navigation system. While procedure time was increased slightly by the use of the navigation system, radiation dose was decreased significantly [1]. In another study of distal locking by Rohilla et al., the average number of fluoroscopy images used for the complete procedure was 48.27 [2], which results in significant radiation exposure. To improve visualization during minimally invasive procedures and reduce radiation exposure, many researchers have proposed augmented reality systems such as video see-through binocular systems [3], half-mirror display devices [4], systems that directly project images onto the patient's body [5], and single laser-beam pointers [6]. However, these systems have some other challenges such as complexity in surgical tool alignment in proper position and orientation.

In many orthopedic surgeries, navigating the surgical tool to the desired target position is crucial. In addition to image-guided navigation techniques, other methods have been investigated, either to augment the available visual information or to provide additional guidance to a conventional surgical approach. An infrared system was used to track the surgical tool position and provide depth guidance during drilling [7]. Simpler mechanical frames, in the form of a physical stopper, depth guide and depth guidance rings have been implemented to constrain the drill depth. Alternatively, a combination of image-guided and robot-assisted navigation would be a reliable method to provide all required information to perform an intervention in the most efficient and precise way. In regards to the placement of implants to treat SCFE, a navigated robotic system could help reduce both screw placement errors and procedure time by allowing more precise screw placement and decreasing the number of fluoroscopic images needed to accurately position the drill guide along the planned trajectory. The goal of this study was to improve screw placement accuracy, and reduce procedure time and intra-operative radiation dose, by developing an image-guided robotic surgical system to assist the orthopedic surgeon with pre-operative path planning and intra-operative drill guide placement.

2 Methodology

A conventional SCFE procedure relies on fluoroscopy to provide the visual feedback needed by the surgeon to accurately place the fixation screw. This exposes the surgeon to significant radiation exposure over their operating lifetime. In addition, the precision of screw placement is highly dependent on the surgeon's skill and ability to visualize the 3D trajectory of the screw from 2D X-ray images. A few millimeters of screw misplacement could potentially lead to major complications. It requires an experienced surgeon to determine the proper position and orientation of the screw and mentally transform the patient space to image space. All these reasons lead us to develop our robotic assist system for the SCFE procedure. The major contribution of this paper is developing and demonstrating an integrated platform for surgeons that assists in path planning by choosing the entry and target point easier and faster. In addition, we aim to increase the precision of screw placement and decrease the time of the SCFE procedure by navigating the robot to align the drill tip position and drill path along a planned trajectory. When the drill guide is at the planned target location, it provides a rigid and constrained trajectory for the drill to advance.

Pre-operative Planning: The surgical workstation uses preoperative CT data to provide a four-quadrant view of the surgical anatomy. The workstation was created using the open source software package the image-guided surgical toolkit (IGSTK)[8]. This four-quadrant view consists of axial, sagittal, coronal and 3D rendered volumetric views, which can be used by the surgeon to define skin entry and final target points for screw placement (as shown in fig. 2).

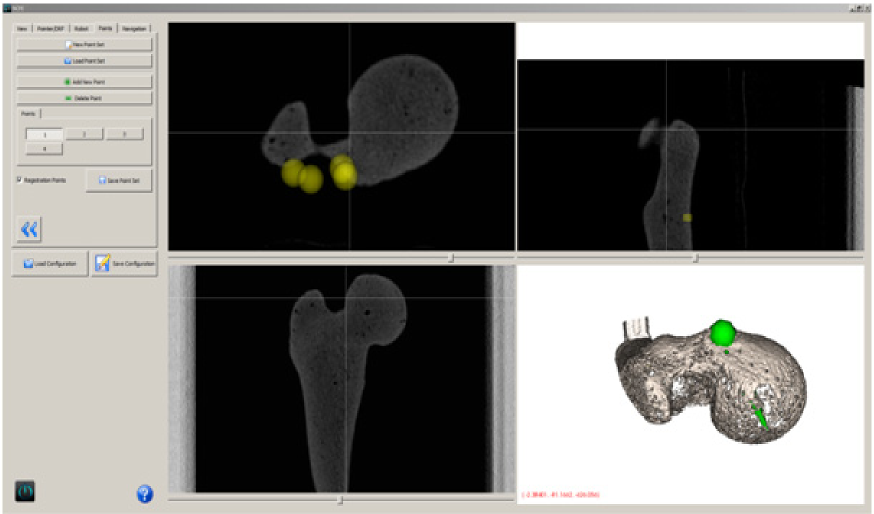

Fig. 2. Surgical navigation workstation showing axial, sagittal, coronal, and 3D views

Trajectory Planning and Calculation of Robot Transformation: The robotic arm used to position the drill guide is a 7 DOF KUKA Light Weight Robot (LWR) robot[1]. The KUKA Fast Research Interface (FRI) API is used to establish a communication between workstation PC and KUKA robot. The application and FRI communication run in parallel using multi-threading. FRI can transfer 20 packets per second which allows the system to update the current position and orientation of the robot in real-time. This update rate means any position change of patient, tracking system, or KUKA base will be compensated quickly via FRI. The surgical navigation component measures the current position of the patient and the robot end-effector and calculates the transformation needed to move the robot from its current position to the planned position. The transformation is then sent to the robot via FRI. A Polaris™ optical tracking system[2] is used to track the locations of the bone phantom and KUKA end-effector and provides a means of computing the transformations between patient and robotic workspace, shown in fig. 3 Two unique rigid body markers, one mounted to the KUKA drill guide tool and one mounted to the bone phantom, are used to track their locations in tracker camera coordinates. The surgical navigation component provides registration between the pre-operative CT dataset and tracker coordinates. This is done using paired-point registration [9] of identifiable phantom surface

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[2] Northern Digital Inc., Waterloo, Canada.

features. The transformation from CT to camera coordinates is then used to transform the skin entry and target points (selected by the surgeon within the surgical planning application) to robot coordinate space. Since the drill guide is aligned precisely to the X-axis of the KUKA, our application finds the angles between the X-axis of KUKA and the line crossing transformed entry and target point by using (1) where “a” is KUKA x-axis and “b” is desired trajectory.

$$\cos\theta = \frac{\bar{a}.\bar{b}}{|a|\times|b|} \tag{1}$$

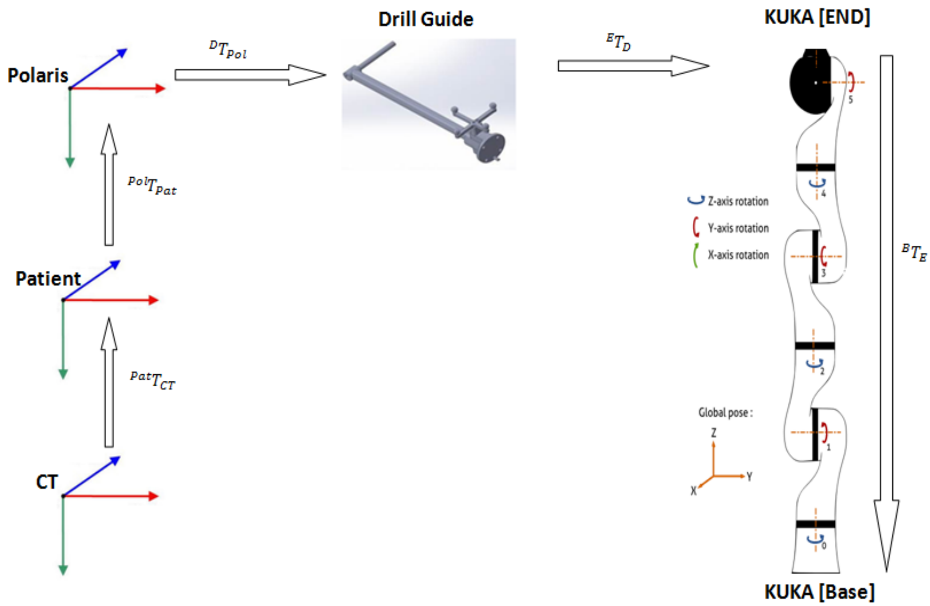

Fig. 3. Chain of transformation from patient coordinate system to KUKA[3] coordinate system

Intra-operative Robot Positioning: A drill guide was designed and fabricated through rapid prototyping[4] to affix to the KUKA end-effector, and securely align the drill along a planned trajectory. The drill guide was designed with a long offset to give the surgeon room to manipulate the drill through the guide. The desired robot end-effector path is converted to joint space using inverse kinematics and communicated to the KUKA controller via FRI. Once the drill guide has reached the commanded position, the KUKA thread inside the application software updates the KUKA coordinates 20 times in one second and calculates the average position and orientation. This helps to reduce the effects of noise in tracker measurements. The

[3] KUKA from `http://www.openrobots.org/morse/doc/latest/user/actuators/kuka_lwr.html`

[4] Objet Connex500, Stratasys Ltd., USA.

robotic arm then maintains its position in a docked state and the surgeon can use the drill to create the pilot hole for screw placement. Several safety concerns have been addressed in this project. First, a virtual region in the KUKA controller has been set in addition to the internal safety features of the KUKA robot. Therefore, the KUKA robot will be turned off if it goes outside of this region. Second, there is a physical stop in the drill guide and a safety offset in the application to prevent the surgeon from drilling beyond a pre-specified depth.

Once the integrated software application was developed, we conducted preliminary tests to assess the contribution of errors from the different system components within the transformation chain. The first proof of concept test conducted in the lab used a CT dataset of a Lego model in the KUKA coordinate system and moved the robot to several predefined points in different orientations. After the lab test, we completed a study in the operating room to position all required devices for image-guided robotic system without any interference with other existing tools and devices. We used 10 pre-scanned sawbones in the operating room test and the surgeon selected entry and target points for screw placement on our interventional workstation. Then we navigated the KUKA to the proper position and the surgeon drilled the wire into the sawbones models.

3 Results

After the initial experiment described above, the overall procedural workflow was tested again and validated in a laboratory environment to get more precise results. First, we redesigned the drill guide to make it stiffer and position the optical tracking frame closer to the tip to minimize offset error. Second, we ran the KUKA robot iteratively to filter the tracking system noise by averaging. The KUKA can receive 20 message packets including new accessible positions and orientations in each second. After system accuracy optimization, additional tests were then conducted in the operating room. Left femur bone models with slipped capital epiphysis deformity were used to perform the drilling and screw placement tasks, as shown in fig. 4. The results from 10 robotic assisted trials performed by an orthopedic surgeon showed sufficient accuracy in comparison to 10 manual trials as detailed below. Of primary note is that all the procedures were done very quickly in these phantom studies, with average times of 4:49 (minutes:seconds). Secondarily, the accuracy results show an overall error that is sufficient for the clinical application [10]. The results are shown in Tables 1- 3.

Table 1. Average time of each step in robotic assisted SCFE surgery phantom experiment (minutes:seconds)

	Planning	Registration	Navigation	Drilling	Total
Average of 10	2:35	0:33	0:43	0:58	4:49

Table 2. Accuracy results (all results in mm). Average of Entry Error and Target error calculated based on distance of desired points and drilled points. Total Error is average of sum of robotic system error and surgeon path planning error for target points.

	Registration Error	Entry Error	Target Error	Total Error
Average of 10	0.588	1.95	2.36	7.04

Table 3. 10 manual trial result conducted by same surgeon. Total Error is measured just for target points based on distance of desired points and drilled points.

	Time	# of fluoroscopy images	Total Error (mm)
Average of 10	2:46	20.4	7.6

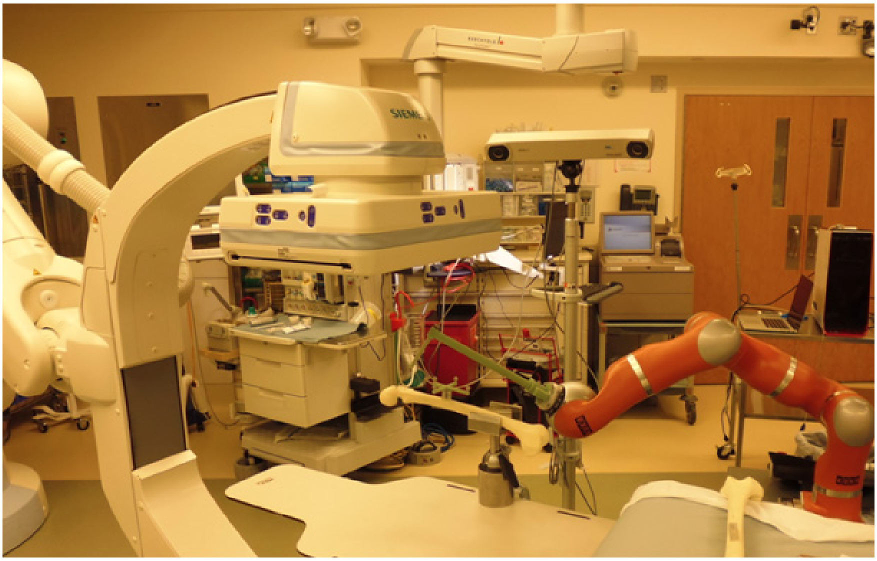

Fig. 4. Phantom study in interventional suite. It demonstrates orange KUKA robotic arm, 3D printed drill guide mounted to the KUKA, bone model and Polaris tracking system.

4 Conclusion and Future Work

Slipped capital femoral epiphysis is a relatively common orthopedic procedure where the accurate placement of the fixation screw is critical to the success of the operation. This paper introduces the system concept and overall architecture for robotically-assisted SCFE procedures. We also present our initial results using phantom models in the operating room. The long term goal is to pursue a clinical trial to determine if this approach could lead to an improved SCFE procedure for patients. For this purpose we also need to improve the workstation and obtain clinical approvals for the system.

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