Robotic System Navigation Developed for Hip Resurfacing Prosthesis Surgery

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Abstract. This paper discusses the design of a navigation system developed to assist surgeons in the procedures of Hip Resurfacing prosthesis surgeries. In conventional surgery, mechanical jigs are used to obtain a correct alignment for the metal prosthesis, however it is a very time consuming process. In order to solve this problem emerges a new robotic system, named *HipRob*. The system is composed by a pre-operative sub-system for planning the prosthesis correct alignment and a flexible robot to be co-manipulated by the surgeon during the drilling procedures on the femur head. The real-time navigation of this robotic system is based on the registration between the femur model, constructed from the CT scan, and the surface constructed with ultrasound images, acquired during the surgical procedures. Experimental results, performed in a femur phantom, show that the robot location errors are around 2 mm.

Key words: Hip Resurfacing, Medical Robotics, Surgical Navigation, Computer-Assisted Surgery.

1 Introduction

The significant improvements of the life quality over the years are only achieved because there are researchers that constantly seek new solutions and new innovative methods to assist clinicians in the diagnosis and procedures. The use of new technologies in medicine allows to improve classical techniques and develop new solutions. These technologies can be used in the clinical diagnosis or in clinical procedures such as surgery. In order to reduce the patient's trauma and recovery times, the traditional open surgery is being replaced by minimally invasive techniques in different surgical procedures. In the other hand, the image-guided navigation systems provides to the surgeons the possibility to tracking surgical instruments based on medical images. It is important to identify the anatomical structures during surgery, understand the target's movements and consequently use these informations in the control loop of the medical robotic systems. These techniques improves the accuracy and reduces the risks of surgical procedures.

This paper is focuses in a new navigation technique for medical robotic systems, developed to assist surgeons in the fields of orthopaedics, in particular to be used in the Hip Resurfacing (HR) prosthesis surgery. The system it was developed to solve a current problem identified by the orthopaedic surgeons who perform HR surgeries. The problem consists in the amount of time spent, during surgery, to obtain the correct alignment to perform an implant in the femur head, with the current techniques. The surgical navigation is based on the patient's Computed Tomography (CT) imaging data, to prepare surgical procedures before operation, i.e., to obtain the desired drilling point needed to implant the initial guide wire. During surgery, to achieve an accurate system to drill the femur head, the robot's surgical drill and the femur movements must be tracked. The surgical drill is tracked through a localizer system, while the femur movements are tracked also using Ultrasound (US) images. This real-time feedback allows to compensate the femur movements, during the bone drilling with the robot, without incisions in the femur.

Much research has been carried out in the fields of medical navigation systems for real time applications. Currently the ultrasound imaging modality has gained a special importance in the intra-operatory scenario due to its portability and the capability to produce images in real time. It is very useful to identify regions of interest and the movements of the anatomical structures that aims to track.

In [1] the US images are used in the guidance of a robotic system in the liver tumor treatment. It is discussed a medical robot guidance system based on ultrasound images to track the target automatically. The precise localization assists the surgeon and improves the surgery success. [2] presents a surgical navigation system based on the IGSTK (Image- Guided Surgical Toolkit) that guides medical robots to drill pedicle screws into vertebra. A Client-Server based architecture supported by OpenIGTLink protocol is used to realize the data transfer between navigation system and a KUKA robot. In [3], the authors present a review of surgery navigation system based on ultrasound guidance. In [4] an ultrasound diagnostic system is used as the navigation system for movable and deformable organs in the abdomen or chest. The authors developed a real-time updated navigation system using 3D ultrasound imaging for laparoscopic surgery. In [5] is presented an investigation to evaluate a new method to digitize pelvic bony landmarks using the ultrasound technology. An imageless Computer-Assisted Navigation System in Total Hip Arthroplasty (THA) has been shown to help increase the accuracy of cup placement. In [6] the authors investigated if a surgical navigation system using intraoperative ultrasound improves the outcomes of lumpectomy and if such a system can be implemented in the clinical environment. In [7] is presented an ultrasound-based navigation procedure for the head-neck-surgery. To conclude, in [8] it is presented a robotic motion compensation system for bone movement, using ultrasound images.

The remaining structure of the paper is organized as follows: Section 1 motivates the purpose of this project. Section 2 describes the materials and methods. The third section describes the experimental results, and the paper finished with a section about conclusions and future work.

1.1 Motivation

An high number of patients with damaged hip have degenerative joint disease (osteoarthritis rheumatoid arthritis and traumatic arthritis) avascular necrosis or developmental hip dysplasia, [9]. In most cases, the patient's quality of life improves significantly with an hip surgery.

Total Hip Replacement (THR) is one of the most successful orthopaedic interventions used nowadays. The femoral head is removed and replaced by a prosthesis. According to the surgeon Derrek McMinn, [10], the THR procedure is reasonably successful in elderly, relatively inactive patients. However, replacement hip joints wear out quickly in younger, more active patients, leading to the revision surgery and associated complications.

HR is a bone preserving alternative method to THR, [11], which maintains the anatomical loading situation of the hip almost unaffected. It is viewed as an alternative to traditional THR for helping patients return to their active lifestyles. Observing Figure 1, significant differences are noted between the prostheses used in HR and THR. HR is a bone-conserving hip procedure contrary to THR. However, the HR surgical technique is considerably more demanding than THR. Retaining the neck and head of the femur, for instance, makes it much harder for the surgeon to expose the socket. Shaping the femoral head appropriately also takes practice and if the surgeon does that poorly, the patient is far more likely to suffer a femoral neck fracture.

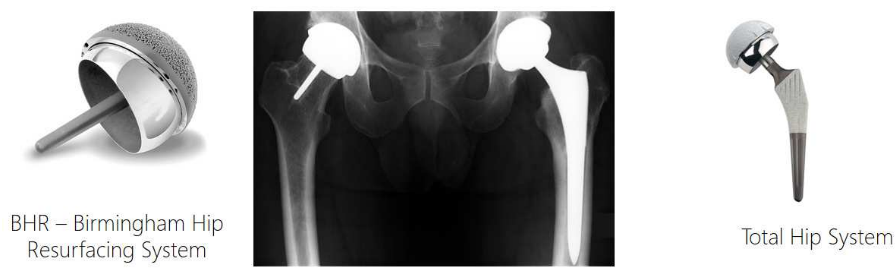

Fig. 1 Prosthesis used in Hip Resurfacing and Total Hip Replacement.

In the Birmingham Hip Resurfacing surgery (designed in Birmingham by Derrek McMinn), the implant alignment is the most important pre-operative consideration for correct implant positioning. According to the surgical procedures, described in, [12], and illustrated in Figure 2, the correct positioning is obtained pre-operatively (step 1), and intra-operatively, the alignment is made from a very time consuming mechanically procedure (step 5), through a alignment guide (named McMinn Alignment Guide). A guide wire is inserted when the desired position of the alignment guide has been achieved (step 6). The guide wire ensures that the spherical metal cap is positioned correctly on the femoral head. The success of the surgery depends on the correct positioning of the guide wire.

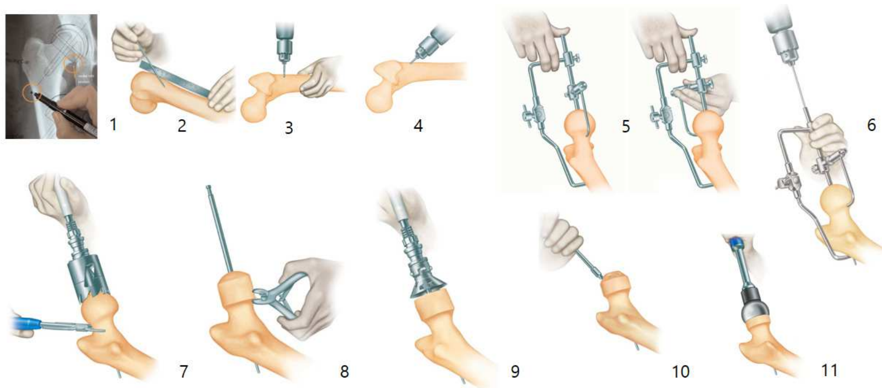

Fig. 2 *smith&nephew*, BIRMINGHAM HIP Resurfacing System (Extracted from [12]).

Several studies have identified the malpositioning as a risk factor for femoral neck fracture after HR, [13], [14], [15], [16]. Computer navigation systems, are an increasingly alternative to allow accurate placement of the femoral implant. Several studies comparing HR procedures performed using mechanical jigs and computer navigation systems, demonstrate that the computer navigation systems allows more accuracy, [17], [18], [19], [20]. Improve the navigation systems and assist surgeons in the HR procedures is the greatest motivation of this project, i.e., to find a robotic solution that increase the accuracy and reduce post-operative complications associated with the technique.

2 Materials and Methods

2.1 Navigation system

Pre-operatively, during the surgery planning, the surgeon defines the correct position and orientation for drill the femur head in order to implant the initial guide wire. Inside the operating room, during surgical procedures, pre-operative (CT) and intra-operative (US) image space must be registered, such that image space can be related directly to the real world coordinate system of the patient. For this reason, registration is the fundamental task in image guided surgery. Figure 3 shows the different coordinate systems of our navigation system. Pre-operatively it is known the target in the CT coordinate system. Intra-operatively there are four different coordinate systems, the referential of the robot, of the bone, of the localizer and of the US probe.

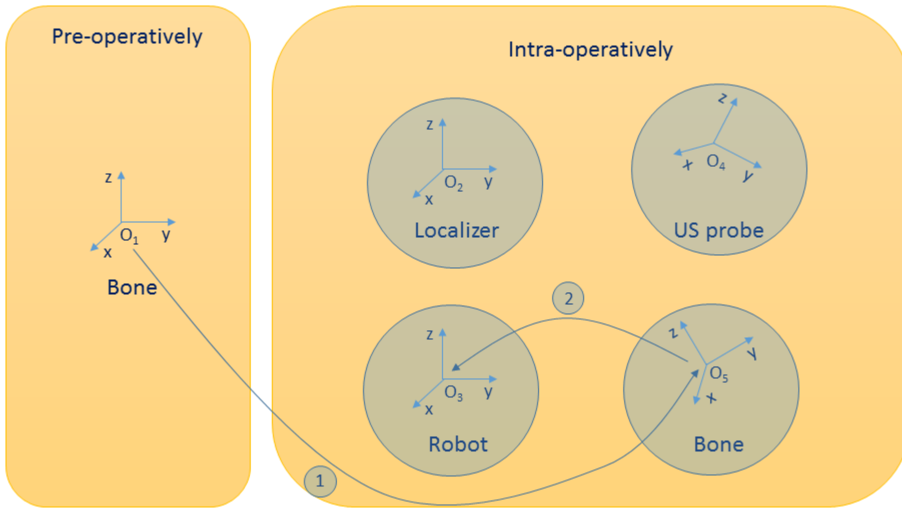

Fig. 3 Coordinate systems, involved in the navigation system.

Steps to identify the femur position and orientation inside the operating room:

1. ***Pre-calibration of the system to localize the femur:***

   a. ***Pre-operatively:***
   - *Do a CT scan of the femur;*
   - *Process the CT images;*
   - *Construct a volume with the 2D image slices;*
   - *Extract the bone point cloud (This point cloud is the bone model);*

   b. ***Acquiring data intra-operatively:***
   - *Perform a scan with the US probe on the femur;*
   - *Synchronize the image plane with the opto-tracker system;*
   - *Define a region of interest (ROI) in the first image acquired;*
   - *Cleaning the ROI with denoising methods;*
   - *Perform the bone contour segmentation;*
   - *Extract the points of the bone upper surface in the opto-tracker's reference frame;*
   - *Construct a 3D surface with the point cloud of each 2D slice;*

   c. ***Registration:***
   - *Reduce the OUTLIERS in both datasets, CT and US through the RANSAC algorithm;*
   - *Perform a global rigid registration through the ICP algorithm (Target: CT, Moved Points: US);*
   - *Perform a locally rigid registration through the ICP algorithm to refine the results;*

- *Obtain the transformation matrix that relates the US data in the referential of CT ($^{CT}T_{NDI}$);*

2. ***Identify the bone movements:***

   a. *Acquiring, processing and extract the point cloud of 10 consecutive US slices;*
   b. *Reconstruct the 3D surface with the point cloud;*
   c. *Calibrate the surface with the $^{CT}T_{NDI}$ matrix;*
   d. *Register the US surface with the CT model;*
   e. *Update the femur pose;*

Steps to update the robot position:

1. *Define the setpoint ($^{CT}P_{drill}$) pre-operatively (ideal drilling point);*
2. *Calculate the setpoint in the robot reference frame;*
   - *Measure the drill pose with the localizer ($^{NDI}T_{ROB}$);*
   - *Calculate the drill point in the robot reference frame $^{ROB}P_{drill}$, knowing the calibration matrix $^{CT}T_{NDI}$ and the femur movements through the on-line registration (TR);*
3. *Perform the trajectory planning for the movements between consecutive setpoints;*
4. *Safeguard that the movements are smooth, don't update points above a certain threshold;*
5. *Move the robot for the new pose;*

As was written earlier, the ideal drilling point is estimated pre-operatively but needs to be spatially located within the intra-operative scenario, in order to be updated in case the femur moves. The drilling point in the CT reference frame is calculated at the beginning of the surgery, performed after the intra-operative calibration ($^{CT}T_{NDI}$), and the drilling point position in the NDI referential frame ($^{NDI}P_{drill}$), according to equation 1.

$$^{CT}P_{drill} = ^{CT}T_{NDI} \times ^{NDI}P_{drill} \tag{1}$$

The new drilling point, calculated in the robot reference frame, considering the movements that may exist in the femur is given by equation 2. The update is sent to the robot controller in order to follow the femur movements, if they exist. The robotic system works on variable impedance control for physical surgeon-robot interaction.

$$(^{ROB}P_{drill})_k = (^{NDI}T_{ROB})^{-1} \times (^{CT}T_{NDI})^{-1} \times (T_R)_k \times ^{CT}P_{drill} \tag{2}$$

where, $(T_R)_k$ is the homogeneous matrix that represent the transformation obtained in the on-line local registration, which updates the calibration to compensate for femur movements.

2.2 Experimental apparatus

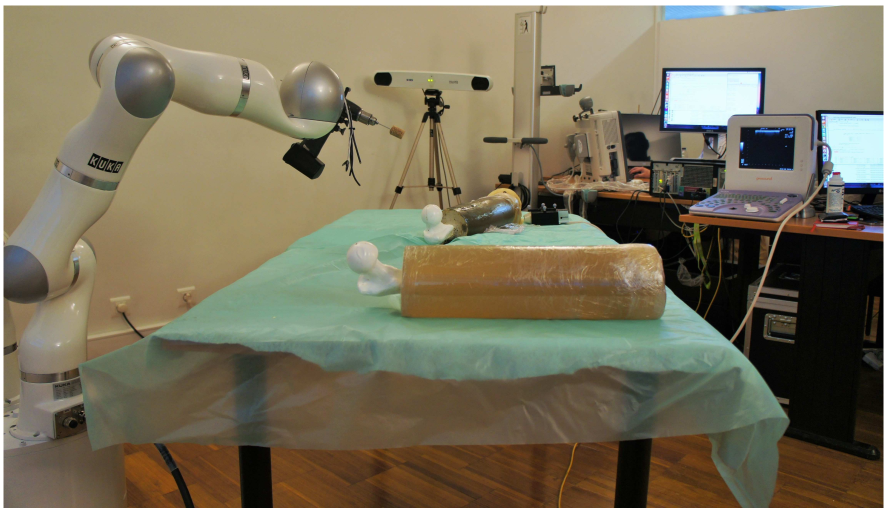

Fig. 4 Experimental apparatus.

Figure 4 shows the experimental apparatus created in the developments of HipRob navigation system. This system consists of of three workstations, an optical measurement system (NDI Polaris Spectra), a portable ultrasound system (Aloka prosound 2), with a 5 MHz linear probe and a USB video frame grabber. The vision-oriented software for bone tracking has been developed in C++ on NetBeans environment running under OS X operating system. This computer, responsible for the Bone Tracking, is connected to the NDI Polaris and frame grabber by USB. The calibration, registration and Navigation applications, run on another computer under Ubuntu Linux operating system. Both applications, calibration and Navigation, have been developed in C++ using the PCL, [21], for 3D point cloud processing, registration and visualization. The third computer receives the updates obtained from the navigation system and implements the trajectory planning, ([22]), for real-time robot control. All computers are connected by Ethernet and communicate via UDP Protocol. To perform experiments of robot positioning in real scenario, it was constructed a femur phantom, visible in the Figure, with similar characteristics to a human femur.

3 Experimental Results

Several experiments were performed in order to validate this navigation system. The experiments were made in a femur phantom, constructed to simulate the drilling procedure. Figure 5 shows the bone tracking during on-line experiments. The red points correspond to the contour resulting of segmentation during the bone tracking. The ROI it is marked in the first acquired image and the algorithm, follows the bone contour during the US scans. In Figure 6 are depicted the registration result of an experiment. The surface model it was constructed with the CT point cloud and the red points correspond to the US point cloud after registration.

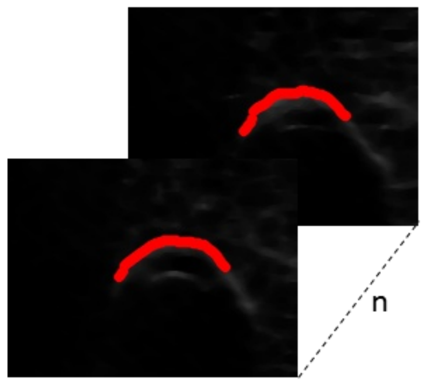

Fig. 5 Bone's contour tracking results obtained during on-line experiments.

Table 1 present the errors obtained in each task that influence the system accuracy. The acquisition errors are particularly associated to wear of the opto-tracker reflective balls. The segmentation it is other task that influences the final result, however in this system it is obtained good results taking into account the type of images. The registration errors are distributed by the calibration and on-line process. Finally the tracking error it is the global navigation system error and the accuracy of the system. The robotic system can compensate the bone movements with errors around 2 mm. This error can be improved, if the errors of the previous tasks decrease.

Table 1 Errors chain.

Acquisition	Segmentation	Calibration	on-line Registration	Tracking
1.33 mm	1.17 mm	0.76 mm	0.68 mm	2 mm

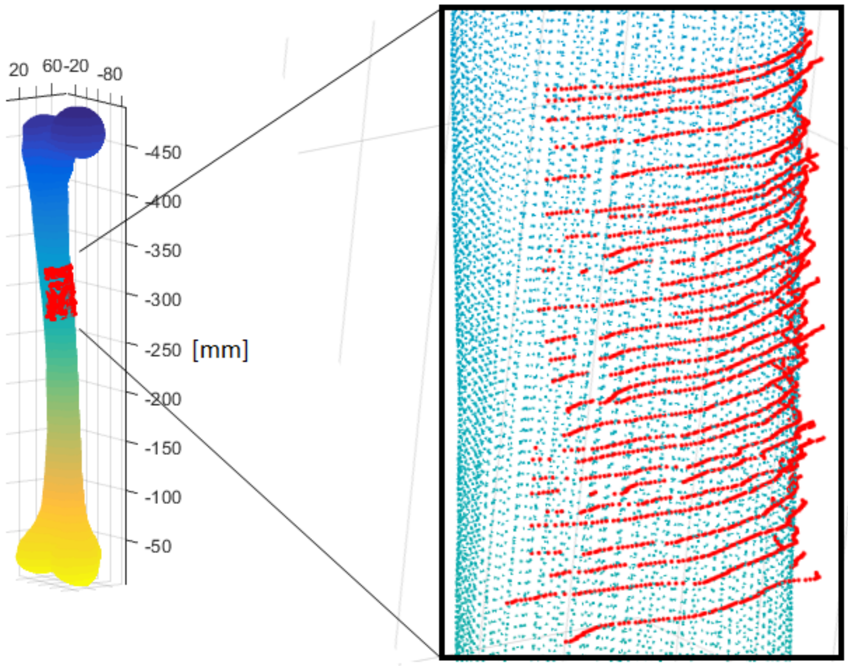

Fig. 6 Bone surfaces after registration. The femur model constructed with the CT point clouds, and the US surface (red) after aligned with the model.

4 Conclusions

The solution developed to track femur bones was successfully applied in a femur phantom. The system can also be adapted to other bone surgeries, that need a precise navigation of the surgical tools. The developed robotic system can compensate for femur movements, during bone drilling procedures. It is useful to ensure the drill desired positioning in order to perform a hole in the femur head, necessary to implant the initial guide wire, which ensures the correct implant's alignment. The robot's navigation system is based entirely on the information extracted from images obtained from CT (pre-operatively) and US (intra-operatively). Contrary to current surgical systems, it does not use any type of implant in the bone, to track the femur movements. The intra-operative bone tracking is performed in real time by registration of 3D US points with the femur 3D model (CT).

A KUKA lightweight robot was used to validate the applicability of the bone tracking system in the experimental tests carried out on a femur phantom. During the experiments the drilling point update was validated, with errors less than 2 *mm* / 3°. This accuracy values are in line with the current conventional alignment systems, which demonstrates that the solution found in this project, is valid and have applicability. The drilling point update, calculated in the reference frame of the robot, is obtained at each 6 seconds.

As future work, the study could be improved if optimized the image acquisition and processing tasks.

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