Computer-Aided Navigation for Arthroscopic Hip Surgery Using Encoder Linkages for Position Tracking

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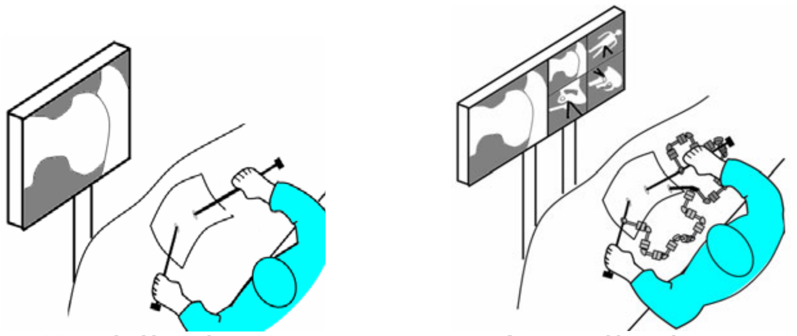
Abstract. While arthroscopic surgery has many advantages over traditional surgery, this minimally invasive surgical technique is not often applied to the hip joint. There are two main reasons for this: the difficulties of navigating within the joint and of correctly placing portal incisions without damaging critical neurovascular structures. This paper proposes a computer-aided navigation system to address the challenges of arthroscopic hip surgery. Unlike conventional arthroscopic methods, this system uses encoder linkages to track surgical instruments, thus eliminating the problems associated with standard tracking systems. The encoder position information is used to generate a computer display of patient anatomy to supplement the restricted view from a typical arthroscopic camera.

Introduction

Arthroscopy is a minimally invasive surgical procedure used to decrease the necessary incision size for joint-repair surgery. Large operative incisions are replaced by small "portal" incisions. A long, thin camera, called an arthroscope, is placed in one portal to display the joint. Additional portals are employed for the insertion of surgical tools. As shown in Figure 1(a), the surgeon navigates by camera images displayed on an operating room screen.

Despite the benefits of arthroscopic surgery, hip arthroscopy is not a common practice as in knee and shoulder repair [1]. In the hip, arthroscopy can be used for removing loose bodies, smoothing rough bone surfaces, and trimming damaged or abnormal tissue [2]. Unfortunately, the hip joint introduces additional challenges for arthroscopy due to the depth of its location in the body, the tight nature of the ball and socket joint, and the proximity of surrounding neurovascular structures. These challenges have created two obstacles for arthroscopic hip surgery: awareness of spatial orientation during joint navigation; and portal incision placement while avoiding damage to critical anatomical structures. The few surgeons who can perform this procedure rely heavily on intuition gained through experience to overcome these challenges.

This research proposes the use of a computer-aided navigation system to ease the difficulty associated with arthroscopic hip surgery. A linkage of encoders is employed to track the motion of surgical tools during an operation. The real-time motion of the tools is shown relative to the patient anatomy on a computer display. These tools provide additional visual feedback to a surgeon for easier joint navigation and safer portal placement during hip surgery. Ultimately, the proposed computer-aided navigation system can increase the use of advantageous arthroscopic procedures over full-incision operations for the hip joint.



(a) Standard hip arthroscopy **(b)** Proposed hip arthroscopy

Figure 1. For current arthroscopy, the surgeon navigates using the arthroscope images only. In the proposed system, encoder chains track instrument position, and an additional screen displays computer images of the instruments and patient anatomy from several viewpoints

2 Previous Work

Although computer-aided tools to assist a surgeon in medical procedures are appearing more frequently, a tool for arthroscopic hip surgery does not exist. Many current computer-aided tools aim to supplement a surgeon's abilities by assisting with accurate and consistent placement of surgical instruments or implants [3-6]. While this research also focuses on the creation of a system to supplement a surgeon's abilities, it addresses the particular issues of portal placement and instrument navigation in arthroscopic hip surgery.

Position tracking is an important component of many computer-aided surgical systems. Although optical and electromagnetic tracking systems are most commonly used, these systems have limitations. An optical system can lose information from its position sensors if the sensor's line of sight to the receiver is broken. Electromagnetic systems are susceptible to distortion or noise from other metallic objects or stray magnetic fields. Due to their associated problems, these typical tracking devices were not employed in the proposed system for hip arthroscopy.

3 System Overview

The basic concept of the proposed navigation system with an encoder linkage is illustrated in Figure 1(b). Instead of a traditional optical or electromagnetic tracking device, a linkage of encoders is introduced as an effective tracking alternative. One end of the linkage is attached to the instrument, while the reference end is attached to a base pin. The base pin is surgically inserted in the patient's pelvis and provides the connection between the linkage and patient. Rotational encoders at each joint location capture the tool motion relative to the patient anatomy.

Given the operative tool positions from the linkage, a real-time display of the surgical instruments relative to the patient anatomy can be generated. The standard arthroscope view of the joint will be supplemented by an additional screen of computer generated images. The additional computer images provide real-time information about the anatomy surrounding the surgical tools as they are manipulated.

For the computer display, a model of the patient's hip joint must be created prior to surgery. Three-dimensional data can be obtained from computerized tomography, magnetic resonance imaging, or a method using x-ray images which has been developed to obtain patient specific models [7]. Also, the position and orientation of the base pin in the patient's hip must be identified for the tracking linkage to correctly locate the surgical tools. The pin will be placed in the pelvis prior to taking x-rays of the patient. Special x-ray markers, like those used in [7], can be employed to determine the camera orientation. The pin can then be located in the model through triangulation with two x-ray images from known view points and orientations.

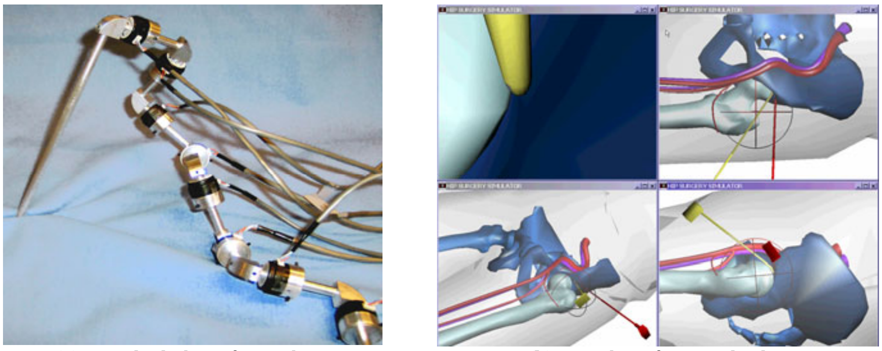
This paper discusses the tracking linkage and the computer display portions of this arthroscopic navigation system. The design for the encoder chain is outlined. Also, the current computer display and associated features are detailed. Finally, the integration of the arthroscopic navigation system with existing surgical equipment is discussed.

4 System Design and Implementation

The encoder linkage for position tracking is kinematically redundant. While a chain with only six degrees of freedom can reach all desired positions and orientations, the chain may be configured such that it encroaches on the surgeon's workspace in some cases. The current linkage, shown in Figure 2, consists of a chain with eight links, each with one rotational degree of freedom. The two additional degrees of freedom provide sufficient flexibility to prevent chain interference.

The main components of the linkage are the L-shaped links, the US Digital E4 encoders [8], and rotational bearings. The 90^{o} bend in the links place the next joint's axis of rotation perpendicular to the previous one. The encoder resolution is 1,200 pulses per revolution, resulting in an accuracy of +/- 0.3 degrees. Adjacent links are attached via a bearing connection.

The position and orientation of the surgical instruments are determined through two main homogeneous transformations. The coordinate frame attached to the endpoint of the chain must be determined in model coordinates. The first coordinate transformation, calculates the tool position relative to the pelvic pin. The eight encoder angles are used to determine this transformation, and it is recalculated to update the tool position each time the encoder angles change. A data acquisition USB device, the USB1, from US Digital [8] was used to obtain the encoder angles. The second coordinate transformation will move from the pin frame to the model frame. This coordinate transformation will be calculated only once, based on the pin position in the 3-D patient model obtained from x-rays [7].



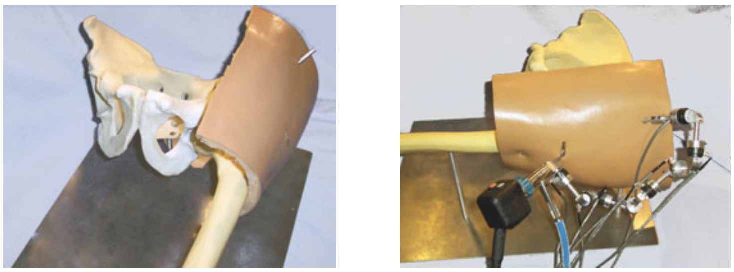
(a) Encoder linkage for tracking **(b)** Snapshot of screen display

Figure 2. Components of proposed navigation system

The screen display shown in Figure 2(b) consists of four windows that display different views of the hip joint and surgical tool models. Narrow cylinders, with rounded ends and rectangular handles, are used to represent the arthroscope (red) and a surgical tool (yellow). The upper-left window of the display is a picture of the model as viewed from the simulated arthroscope. This window mimics the actual camera image currently used by the surgeon. The remaining three windows show the model from different perspectives as set by the surgeon.

As the encoder angles change, the screen images are updated to reflect a new instrument position. The screen display update rate is limited by the speed at which the new transformation matrix can be calculated and the graphics can be redrawn. The program currently runs on a computer with a 2.2 MHz AMD64 processor, 1.0 GB RAM and a NVIDIA GeForce 6800 GT video card. With this computer, the screen updates approximately every 78 ms or almost 13 frames per second.

The computer-aided navigation system was integrated with standard arthroscopic equipment on a mockup of the human hip joint as shown in Figure 3. The standard system consists of a Sony video monitor, a 4mm, 70^{o} Video Arthroscope, a Dyonics Xenon light source for the arthroscope, and a Dyonics Vision 325Z Camera System. The video monitor displays the arthroscopic camera images. The arthroscope is connected to the light source by a fiber optic cable, and to the vision system via the camera head. With the addition of the navigation system, the arthroscope also has a connection to the tracking chain.



(a) Model of human hip joint **(b)** Arthroscope and linkage applied to model

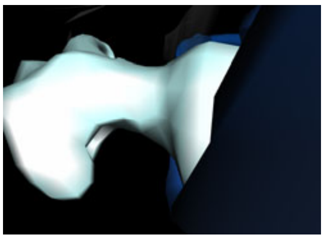
Figure 3. Hip model and arthroscope connections. The arthroscope is connected to both the tracking chain and traditional arthroscopic equipment (camera head and light source).

5 Position Error of Encoder Chain

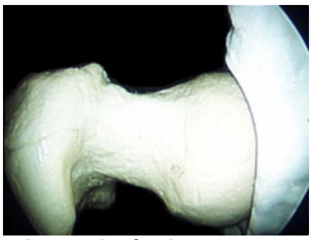
An accuracy estimation of the tracking system can be observed through the comparison of the camera and computer images. The computer image in the upper left of the display window (Fig. 2(b)) should match the image displayed on the video monitor from the arthroscope. Using both the computer navigation system and the Smith and Nephew equipment on the hip model, simultaneous images were collected from the computer screen and the video monitor for comparison. Figure 4 displays an example of the resulting comparison.

The arthroscope images obtained from the arthroscopic camera and the computer program are very similar, but do not match exactly for several reasons. First, the computer hip model and physical hip model are not identical in the demo system. For an actual procedure, the three dimensional model would be taken from the patient to ensure agreement between the models. Some error is also attributed to the inexpensive encoders used in the current demonstration system. Finally, the initialization method for the chain can contribute to image discrepancies. If the chain is not positioned precisely during the initialization, the calculated transformation matrix for the chain will be incorrect.

Considering error in the encoder readings, the worst case error will occur when the chain is fully extended and all encoders record the maximum error value. The maximum error of 0.3^o is a result of the encoder resolution. When the chain is fully extended, any error in the measured angles will have the greatest effect since the effective chain length is at its largest. In this worst case, the accumulating error will result in the chain endpoint being approximately 5mm from the reported location. However, the chain has been sized such that it is not frequently in the fully extended configuration for hip arthroscopy maneuvers. Also, the errors in the chain measurements can occur on opposite directions, decreasing the overall endpoint error as the individual errors somewhat cancel. The error can also be decreased by selecting encoders with higher resolution.



(a) Simulated 70^o-arthroscope view



(b) Actual 70^o-arthroscope view

Figure 4. Comparison of arthroscope views from the simulated and the actual arthroscope.

4 Conclusions

The navigation system for arthroscopic hip surgery can be used as a tool to address the challenges of joint navigation and portal placement in arthroscopic hip surgery. In the operating room, the system can visually supplement the limited view from the arthroscope. Specifically, a surgeon can view the location of his tools relative to the patient anatomy and be warned when tools enter dangerous regions.

The introduction of a tracking linkage shows significant potential as an alternative to more expensive and often problematic tracking systems. The encoder linkage for position tracking eliminates problems associated with optical and electromagnetic systems in medical applications. The redundant linkage provides the required flexibility for arthroscopic maneuvers while tracking the surgical instrument position.
Positive feedback about the completed demo system was obtained from surgeons who perform arthroscopic procedures [9]. The encoder linkage was seen as an acceptable addition to the surgical workspace, and the extra visual feedback was considered valuable.

Next steps of this project include a more rigorous examination of the linkage error, the creation of a new encoder chain, changes to the computer display, and user studies. The chain will use more accurate and smaller encoders. In addition, absolute encoders will be employed instead of incremental encoders. Using absolute encoders will simplify of the linkage initialization and eliminate this source of error. For the computer display, future work involves obtaining matching computer and physical hip models. With identical models, it will be possible to analyze the accuracy of the system in more detail. Finally, feedback about the system will be sought through user studies.

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