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ORIGINAL ARTICLE

Computer-aided navigation for arthroscopic hip surgery using encoder linkages for position tracking†

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Abstract

Background While arthroscopic surgery has many advantages over traditional surgery, this minimally invasive technique is not often applied to the hip joint. Two main reasons for this are the complexity of navigating within the joint and the difficulty 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.

Methods Unlike conventional arthroscopic methods, our system uses a hyper-redundant encoder linkage to track surgical instruments, thus eliminating the occlusion and distortion problems associated with standard optical and electromagnetic tracking systems. The encoder linkage position information is used to generate a computer display of patient anatomy.

Results The tracking error from the encoder linkage was evaluated to be within an acceptable range for this tracking prototype, and the new computer-aided approach to arthroscopic hip surgery was applied to a prototype system for concept verification.

Conclusion This 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 by visually supplementing the limiting view from the arthroscope. The introduction of a tracking linkage shows significant potential as an alternative to other tracking systems. Positive feedback about the completed demo system was obtained from surgeons who perform arthroscopic procedures. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords hip arthroscopy; minimally invasive surgery; surgical tracking; computer aided surgery

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. While, a 15–25 cm opening is necessary to fully expose the hip joint using traditional methods (1), arthroscopy only requires two or three portals of approximately 6–7 mm (2). A long thin camera, called an arthroscope, is placed in one portal to display the joint area that is usually exposed by the full-size incision. Additional portals are employed for the insertion of surgical tools. As shown in Figure 1, the

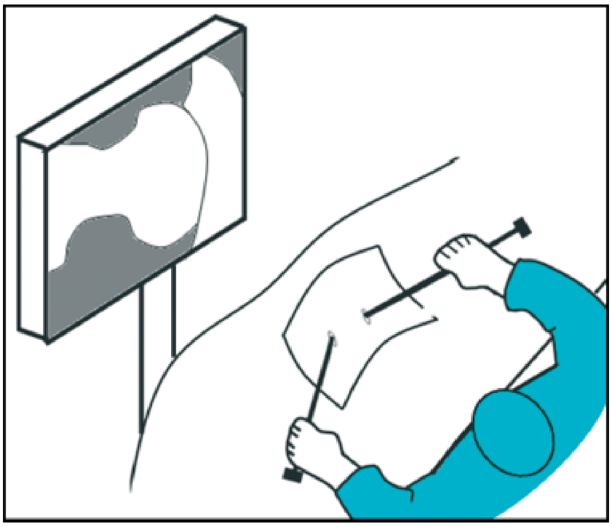

Figure 1. Standard arrangement for hip arthroscopy. An arthroscope and other surgical tools are manipulated by the surgeon through small portal incisions in the patient. The surgeon navigates using the arthroscope image displayed on a computer screen in the operating room

surgeon navigates a surgical tool by using only camera images displayed on an operating room screen.

Arthroscopy was initially introduced as a diagnostic tool, but now has significant advantages for many joint repair procedures (3). Advantages such as a faster recovery time, shorter hospital stay, less soft tissue trauma, less blood loss and a lower incidence of infection make arthroscopic surgery more desirable than traditional full-incision operations (1). Hip arthroscopy can be used for removing loose bodies, smoothing rough bone surfaces and trimming damaged or abnormal bone and tissue (2). Also, minimally invasive treatment of early hip problems could decrease or delay the onset of other more serious hip conditions (4,5).

Despite the benefits of arthroscopic surgery, arthroscopy is not as common in hip repair as in knee and shoulder repair. The hip joint introduces additional challenges for arthroscopy. For example, the hip joint is located deeper within the body than joints such as the knee or shoulder. Also, the ball-and-socket geometry of the joint provides a very tight working envelope. Finally, there are an increased number of surrounding muscles, ligaments and neurovascular structures to consider in the case of the hip joint.

The challenges associated with the hip have created two particular obstacles for arthroscopic hip surgery: awareness of spatial orientation during joint navigation; and portal incision placement while avoiding damage to critical anatomical structures. Although the arthroscope allows the surgeon to observe the joint, extra skill is required to associate the camera image with the actual patient anatomy for navigation. This is a common problem for other minimally invasive surgeries (MISs), including MIS hip replacement and laparoscopic procedures (1,6). Instrument placement is a critical step in establishing the desired arthroscope viewing area. Multiple arteries, veins and nerves populate the area in which the portal incisions are placed. The surgeon's challenge is to create incisions that provide appropriate access to the joint but do not harm the sciatic nerve, femoral artery or femoral vein. Surgeons who 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, and the real-time motion of the tools is shown relative to the patient anatomy on a computer display. A visual warning informs the doctor of dangerous surgical manoeuvres. 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 in the hip joint.

Previous work

Computer-aided tools are appearing more frequently to assist in medical procedures and as training simulators. For example, hip replacement systems enable the surgeon to place implants more accurately and consistently (7,8). A system for minimally invasive coronary bypass surgery assists with incision accuracy and visualization of the tool within the patient (9). Training simulators are currently under research for procedures such as laparoscopic and minimally invasive heart surgery (6,10). While these and other tools have been introduced to supplement a surgeon's abilities, a similar tool for arthroscopic hip surgery does not exist. Our system focuses on 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. Optical and electromagnetic systems are the most common types of tracking devices, but these systems have limitations. For instance, an optical system can lose information from its position sensors if the line of sight to the receiver is broken. Optical systems such as those provided by Northern Digital Inc. or Advanced Realtime Tracking (ART) are more accurate than electromagnetic systems for medical applications, but are relatively expensive (12–14). While less expensive, electromagnetic systems are susceptible to distortion or noise from other metallic objects or stray magnetic fields. More complex or hybrid systems which combine both technologies are currently under research (11).

Mechanical tracking systems avoid the occlusion and distortion issues, but few mechanical systems exist. The few available products, such as the Faro Arm (15), are too large and heavy to be easily manipulated. Due to their associated problems, the existing tracking devices listed above are not employed in our proposed system for hip arthroscopy.

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System overview

The basic concept of the proposed navigation system with an encoder linkage is illustrated in Figure 2. Instead of a traditional optical or electromagnetic tracking device, a linkage of encoders was developed as an effective tracking alternative. One end of the linkage is attached to the instrument, while the reference end is attached to the base pin. The base pin is surgically inserted in the patient's pelvis and provides the connection between the linkage and the patient. Rotational encoders at each joint location capture the tool motion relative to the patient anatomy.

For the computer display, a model of the patient's hip joint must be created prior to surgery. Three-dimensional (3-D) data can be obtained from computerized tomography, magnetic resonance imaging or a recently developed method using X-ray images to create the patient-specific model (16). 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, such as those used in (16), can be employed to determine the X-ray machine orientation. The pin can then be located in the model through triangulation with two X-ray images from known orientations. Different linkage attachment orientations to the pin are possible, provided the orientation is known and calibrated to match the computer software.

Given the operative tool positions from the tracking linkage, a real-time display of the surgical instruments relative to the patient anatomy can be generated. Traditional arthroscopic surgery limits the surgeon's view to only the camera image of the joint. The additional screen of computer images provides supplementary real-time information about the anatomy surrounding the surgical tools. Finally, a warning can be displayed if the surgeon's tools move into a region that may harm the patient. Additional visual information is especially valuable, since most surgeons rely predominantly on visual feedback during surgery (17).

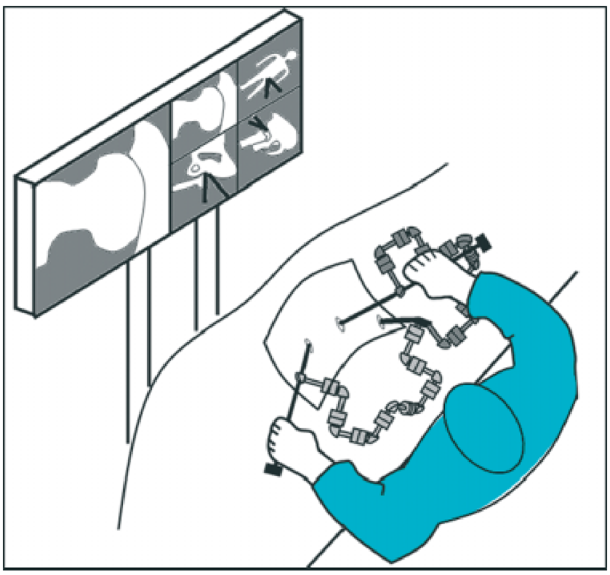

Figure 2. A computer-aided navigation system for arthroscopic hip surgery using a linkage tracking mechanism. Two encoder chains track the position of the surgeon's arthroscope and other tools. An additional screen in the operating room displays computer images of instruments and the patient anatomy from multiple views

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

System design and implementation

Encoder linkage for position tracking

Because all tool motion is limited around the portal incisions, the use of a tracking linkage is well suited to arthroscopic surgery. The portals themselves prevent significant instrument motion; thus, a flexible encoder linkage will not unduly interfere with the arthroscopic procedure. Also the linkage length can be optimally designed, since the portals are only made in specific anatomical locations.

The encoder chain was created as a redundant linkage, which has additional degrees of freedom, to ensure minimal interference by the chain. 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 in Figure 3a consists of a chain with eight links, each with one rotational degree of freedom. The two extra degrees of freedom provide sufficient flexibility to prevent chain interference without adding unnecessary degrees of freedom. As shown in Figure 3b, the linkage lies against the patient and does not protrude into the working area.

The main components of the linkage, as diagrammed in Figure 4, are the 'L'-shaped links, the US Digital E4 encoders (18) and the rotational bearings. The 90° bend in the links place the next joint axis of rotation perpendicular to the previous joint axis. The encoder diameter is 2.16 cm (0.85 in), with a resolution of 300 counts/revolution. Using the encoder's two-channel quadrature output, 1200 pulses/revolution are achieved. The encoders have three parts: the base, with the light source and receiver; the encoder disk, with alternating reflective and non-reflective bands to quantify rotation; and a protective outer cover. The base of the encoder is fixed to a plate connected to one link while the encoder disk is attached to the next link in the sequence. Thus, the encoder measures the rotation between links as the disk rotates relative to the encoder base. Finally, adjacent links are attached via a bearing connection with full 360° motion. Although the external power and data transmission cables can hinder excessive

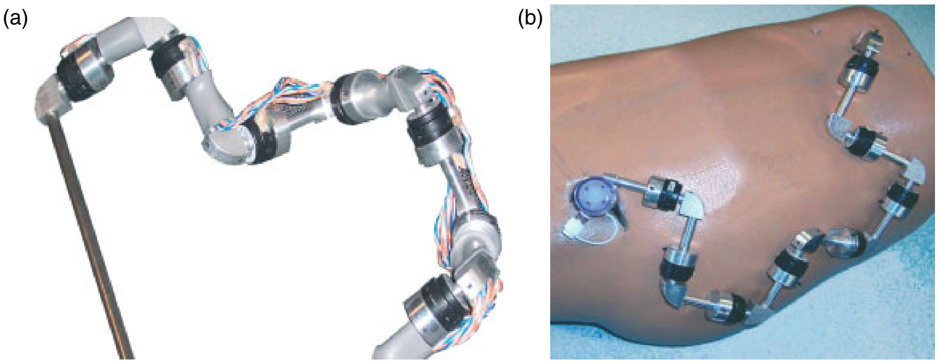

Figure 3. Encoder linkage for position tracking. (a) Tracking linkage prototype. (b) Linkage applied to a hip model. The linkage is redundant with extra degrees of freedom, to increase flexibility and ensure that the linkage remains out of the surgeon's work space

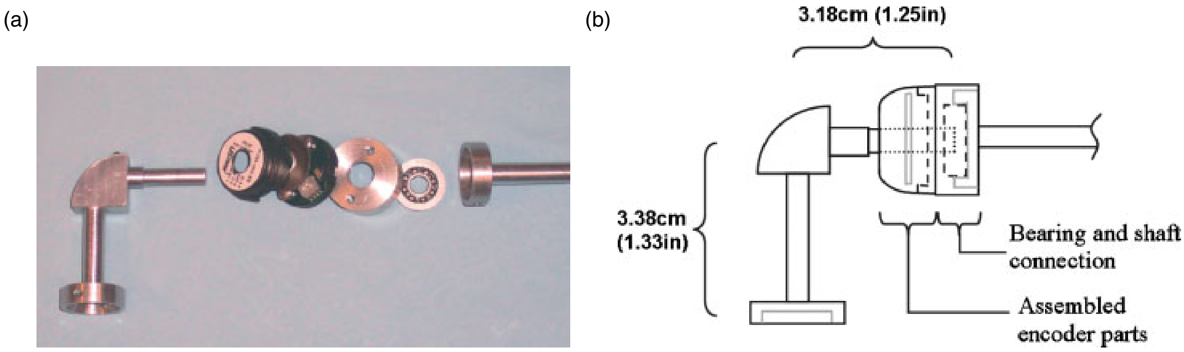

Figure 4. Encoder link components (a) and assembly. (b) Diagram of the assembled link

rotation, each link actually rotates within a small range of angles, due to the extra degrees of freedom in the chain.

Data acquisition and computer display

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 transform, T_1, calculates the tool position relative to the pelvic pin. The eight encoder angles are used to determine this transformation, and T_1 is recalculated to update the tool position each time the encoder angles change. A data acquisition USB device, the USB1 from US Digital (18), was used to obtain the encoder angles. A second transform, T_2, moves from the pin frame to the model frame. This transform will be calculated only once, based on the pin position in the 3-D patient model obtained from X-rays (16).

Since the encoders are incremental, they must be initialized to mark a 0° rotation at a known location. The linkage is placed on the initialization device shown in Figure 5, which is a precisely machined plate with an attachment pin and chain-positioning posts. The chain is fixed into the initialization device for an accurate position of the chain before its use. Based on the known configuration for the initialization, the encoder angles are used to determine the transformation matrices for the end point of the chain relative to the hip base pin.

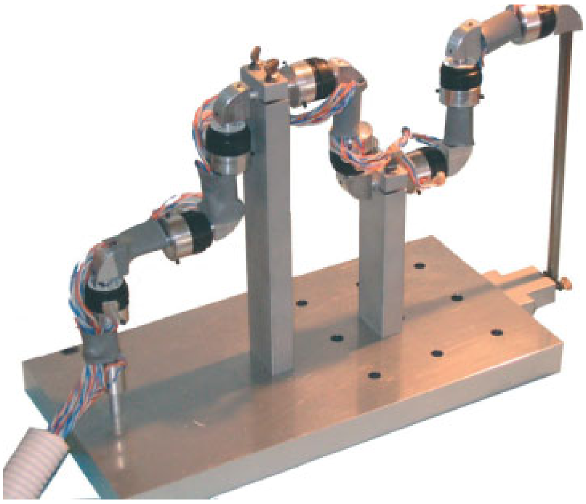

Figure 5. Tracking linkage locked in initialization configuration

The screen display shown in Figure 6 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 (Figure 6a) displays 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 (Figure 6b–d) show the model from different perspectives as set by the surgeon. Depending on the specific procedure, the optimal view to observe patient anatomy can be selected.

As the encoder angles change, the screen images are updated to reflect the 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/s.

The view from an arthroscopic camera is often even more difficult to interpret because the camera does not look directly in the axial direction, but at an angle to the axial direction. Standard viewing angles are 30° and 70°, as shown in Figure 7a. There is a significant difference between a 0° and 70° (most common) viewing angle, as demonstrated by Figure 7b, c. Both images were captured with the tool in the same position and orientation, but with different viewing angles. Since it is often more intuitive to navigate with a 0° viewing angle, the arthroscope view on the computer display can be toggled between the actual arthroscope viewing angle of 70° and the axial direction.

During portal placement, there is concern about harming the patient's critical neurovascular structures. Thus, some of these structures, such as the femoral artery, femoral vein and ascending branch of the lateral circumflex artery, are incorporated into our computer model. To reduce the risk of injury to these structures during portal placement and other surgical manoeuvres, visual feedback has been added to warn the surgeon when tools move too close to the femoral artery and vein or the sciatic

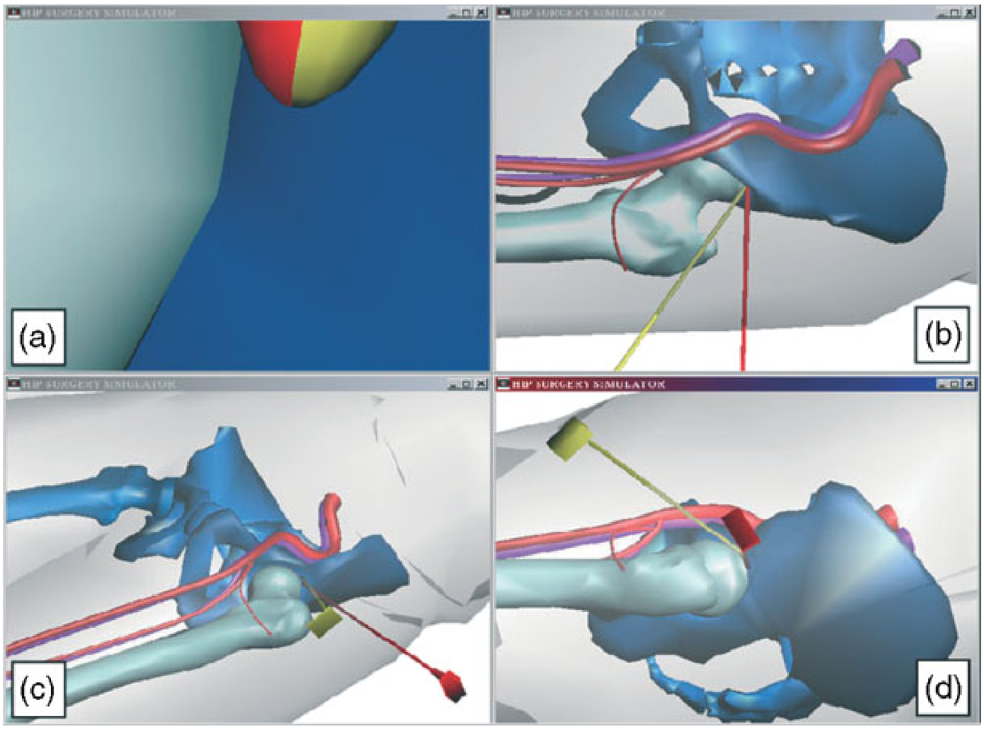

Figure 6. Computer screen display. (a) Window showing the simulated arthroscope view. (b–d) Computer-generated views of hip from alternative perspectives; windows (b–d) can be modified by the user to show a desired viewpoint

Figure 7. Comparison of arthroscopes with varying viewing angles. The camera angle describes the camera viewing direction; the angle is measured from the axial direction of the tool to the viewing direction. (a) Arthroscopes with 0° (top), 30° (centre) and 70° (bottom) viewing angles. (b) Computer-generated view from arthroscope with 0° viewing angle. (c) Computer-generated view from arthroscope with 70° viewing angle

nerve as demonstrated in Figure 8. An 'unsafe region' was defined for the arthroscope and other tools. The arteries and veins are located inside this region. Because these neurovascular structures will shift some amount during the operation, the unsafe region is not defined as the exact geometry of the structures, but as a larger volume which encompasses them. If the surgical instruments move close to the vascular structures and depart from the defined safe region, the screen background changes from white to red as a warning. The surgeon can select the areas to avoid for an optimal surgical result.

Integration with arthroscopic surgical equipment

To integrate the new arthroscopic navigation system with existing arthroscopy equipment, a mock-up of the human hip joint was created. The model in Figure 9a consists of a mounted femur, pelvis and a foam skin covering. A pin was placed in the pelvis as the base for the tracking chain. A small hole in the skin model acts as the portal incision.

The computer-aided navigation system was integrated with commercial arthroscopic equipment. The standard equipment includes a Sony video monitor, a 4 mm 70° 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. In Figure 9b, the arthroscope is connected to the light source by a fibre-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.

When integrating the two systems, a comparison of the camera and computer images can be made. The computer image in the upper left window (Figure 6a) should match the image displayed on the video monitor from the arthroscope. Using both the computer navigation system and the Smith & Nephew equipment on the hip model, simultaneous images were collected from the computer screen and the video monitor. Figure 10 displays an example of the resulting comparison. It should be noted that the arthroscopic image presented in this example is a much clearer image than typically obtained during surgery, when surrounding body structures prevent the surgeon from obtaining this wide, clear view.

Encoder linkage position tracking error

The images obtained from the arthroscopic camera and the computer program in Figure 10 are very similar,

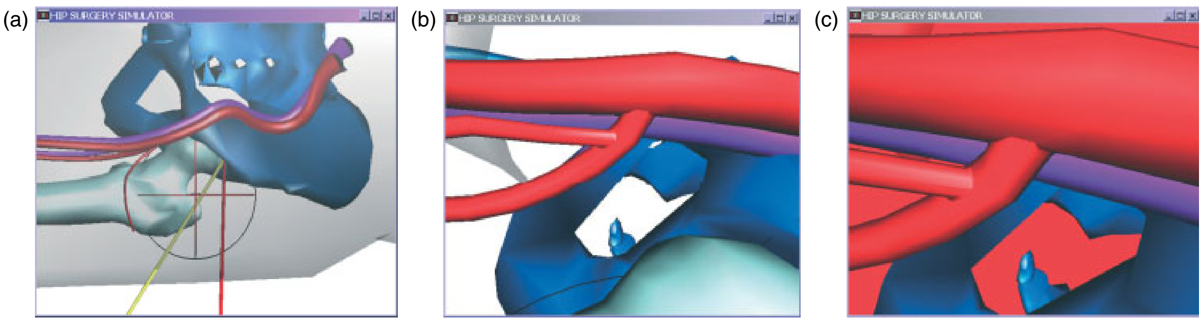

Figure 8. Proximity warning system. (a) Sphere representing safe area for tool operation. (b) Arthroscope view from within the safe sphere. (c) Arthroscope view from outside the safe sphere. As the arthroscope moves outside of the spherically-defined safe region and toward the femoral artery, the screen background changes to red to warn the surgeon

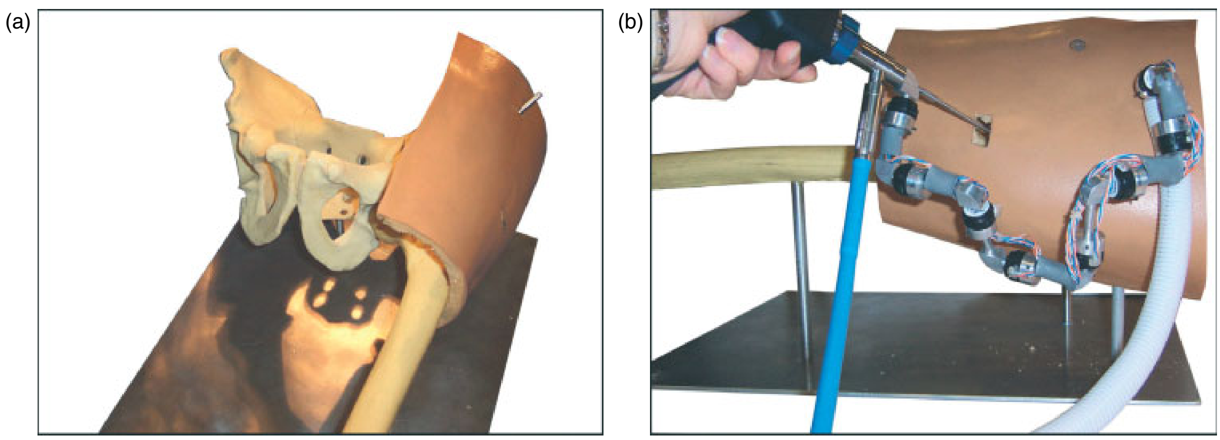

Figure 9. Hip model and arthroscope connections. (a) Model of human hip joint. (b) Arthroscope and linkage applied to model. The arthroscope must be connected to both the tracking chain and traditional arthroscopic equipment (camera head and light source)

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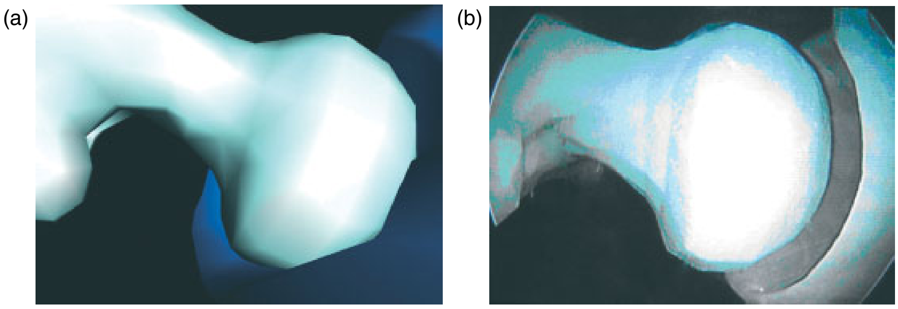

Figure 10. Comparison of arthroscope views from computer-generated display and the actual arthroscope. (a) Generated 70° arthroscope view. (b) Actual 70° arthroscope view

but do not match exactly due to several sources of error. One main source of error is the encoders' finite resolution. The small errors associated with each encoder's resolution will accumulate to decrease the overall linkage accuracy. A second source of error results from the initialization method for the chain. If the chain is not positioned precisely during initialization, the calculated transformation matrix for the chain will produce inaccurate position values.

The encoder linkage position error was tested using the device from the initialization step. The steel rod at the end of the linkage represents a generic surgical tool, and can be inserted into the grid of machined holes, as shown in Figure 11. The chain was initialized as in Figure 5 and then released to place the tool into a selected hole. The calculated tool position was determined from the encoder measurements and compared to the known location of the machined hole. Keeping the position error within 1 mm is the target for the overall system (personal communication, Philippon MJ, Fu FH, 2004).

Two sets of data were collected for analysis. For both cases, 10 measurements were taken from four different holes, resulting in 40 position measurements. In the first case, the chain was initialized between each measurement. The error was determined by calculating the distance between the measured position and the known hole position. This data set considers the absolute error resulting from both the chain initialization and encoder readings. In the second test, the chain was only initialized once at the start of the 40 measurements. In this case, the error was calculated as the distance between the measured position and average position of the measured data. This set of data eliminated the error from the initialization method to consider the only the precision and repeatability of the linkage.

The first case investigated the chain's absolute accuracy, while the second case looked at the chain's precision. The error for the first case was higher than the second case, as listed in Table 1. Given the higher error from the first set of data, the initialization of the chain contributes significantly to the 5 mm error in the absolute position. Since the chain can be calibrated to eliminate the absolute error and correct the accuracy, the precision data from the second case is of greater interest. The error in the second case is within the 1 mm target. As long as a calibration is performed, the precision data of the second case indicates that the average chain error is within the target value.

While the measured error values from this initial prototype show promise, it is necessary to further investigate and decrease the total error. This work does not address the error resulting from sources such as link length variation from machining and assembly, or wear on the linkage or attachment mechanisms. A simple method to reduce the error discussed in this study is to select encoders with a higher resolution. In addition, since the encoders can take data at a rate much faster than the rate at which the screen is updated, averaging multiple position measurements may also produce better error results.

Figure 11. Encoder linkage with generic tool inserted in one of machined holes

Conclusion

This 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 limiting view from the arthroscope. Specifically, a doctor

Table 1. Measured error results

	Case 1: multiple initializations	Case 2: single initialization
Average error (mm)	5.29	0.75
Standard deviation (mm)	0.82	0.55

can view the location of his tools relative to the patient anatomy and be warned when tools enter dangerous regions. This system could also provide an opportunity for medical students to learn and practise the arthroscopic hip procedure.

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 manoeuvres while tracking surgical instrument position. Finally, testing of this initial chain revealed promising error results.

Positive feedback about the completed demo system was obtained from surgeons who perform arthroscopic procedures. The encoder linkage was seen as an acceptable addition to the surgical workspace, and the extra visual feedback was considered valuable (personal communication, Philippon MJ, Fu FH, 2004). Continued input from surgeons will further influence the creation of a second system prototype.

Next steps on this project include the creation of a new encoder tracking linkage, changes to the computer display, and user studies. The second-generation encoder linkage will aim to further investigate and reduce the position error through improved mechanical design and the eventual use of absolute encoders. Absolute encoders will eliminate the need for the initialization step, and associated error, due to the incremental encoders. In addition, a more aesthetic design for the chain will also be considered. For the computer display, future work involves obtaining matching computer and physical hip models. Finally, feedback about the system will be sought through detailed user studies.

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