Verifying the Effectiveness of a Computer-Aided Navigation System for Arthroscopic Hip Surgery

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Abstract. Computer-aided technology can decrease the difficulty associated with arthroscopic surgery. Unlike a larger incision that exposes the whole joint, a small arthroscopic incision limits the surgeon to view the joint only from the arthroscope. Our computer-aided system for hip arthroscopy addresses this loss of joint visibility by (1) tracking tool position with a linkage of encoders, and (2) indicating the tool position relative to the patient anatomy. This paper presents a study of user performance to verify the effectiveness of this computer-aided system for hip arthroscopy. A user study was completed to determine if the computer-aided system could help reduce task completion time and tool path length. Ten participants completed a simple navigation task with and without the assistance of the computer-aided system. A time reduction of 38% and a 72% tool path-length decrease was achieved with the computer-aided system, confirming its effectiveness.

Keywords. Hip arthroscopy, surgical tracking, user-study, computer-aided surgery

Introduction

Although arthroscopy beneficially decreases incision size, it increases surgical complexity due to the loss of joint visibility [1, 2]. The small arthroscopic incision limits the surgeon to view the joint only from an arthroscopic camera. Awareness of spatial orientation while navigating within the joint requires more experience with only the image from the arthroscope. In addition, placing small incisions such that they provide access to the joint, yet do not damage surrounding neurovascular structures is difficult.

As compared to the knee and shoulder, arthroscopy challenges are magnified in the hip [3]. 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.

While several computer-aided systems for arthroscopy have been developed in recent years, the majority of these systems have been developed for knee arthroscopy. Systems like the knee arthroscopy simulators of Heng et al. and Zhang et al., focus on the creation of a training system for inexperienced doctors or students [4, 5]. Other systems such as the one developed by Dario et al. has been developed to aid in visualization during knee surgery [6].

Our computer-aided solution to the challenges particular to hip arthroscopy has been developed using a novel encoder linkage for position tracking [7]. The linkage attaches to a surgical tool and tracks its location relative to the patient anatomy. Then, the position information from the linkage is sent to a real-time display of the tools within the hip joint. In addition to the traditional view from an arthroscopic camera inside the body, a surgeon can view his tool location from multiple angles on the computer display. The additional images return the joint visibility which normally requires a large incision.

This paper discusses the effectiveness of our developed computer-aided navigation system as determined through the use of a user study. In the following sections of this paper, we provide an overview of the system, and then discuss the physical setup for the user study, the tasks for each participant, the resulting user data, and finally some discussion of the results.

1. Overview of the Computer-Aided Navigation System

Our computer-aided system is briefly described here to facilitate a complete understanding of the presented user study. A detailed work on the computer-aided arthroscopic hip surgery system can be found in [7]. Fig. 1 shows the completed prototype system from [7].

The goal of the developed system is to decrease the difficulty associated with arthroscopic hip surgery by increasing the visual feedback to the surgeon. Multiple images of the patient's hip are provided in addition to the view from the arthroscopic camera. The position of the surgical tools is tracked and also included in the images. The additional images allow the doctor to navigate surgical tools within the joint in a more intuitive manner. Also, they increase patient safety by clearly showing the location of critical neurovascular structures.

Instead of a traditional optical or electromagnetic tracking device, a linkage of encoders was developed as an effective tracking alternative. The encoder chain was created as a redundant linkage, which has additional degrees of freedom, to minimize the interference to the surgeon from the chain. One end of the linkage is attached to the surgical 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 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 [8]. 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.

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. The additional screen of computer images provides supplementary real-time information about the anatomy surrounding the surgical tools. The four windows in Fig. 1 display the hip joint from multiple angles for the surgeon. The upper left window is a computer generated version of the view from the actual arthroscope. The remaining three windows can be adjusted to show the hip from any desired angle.

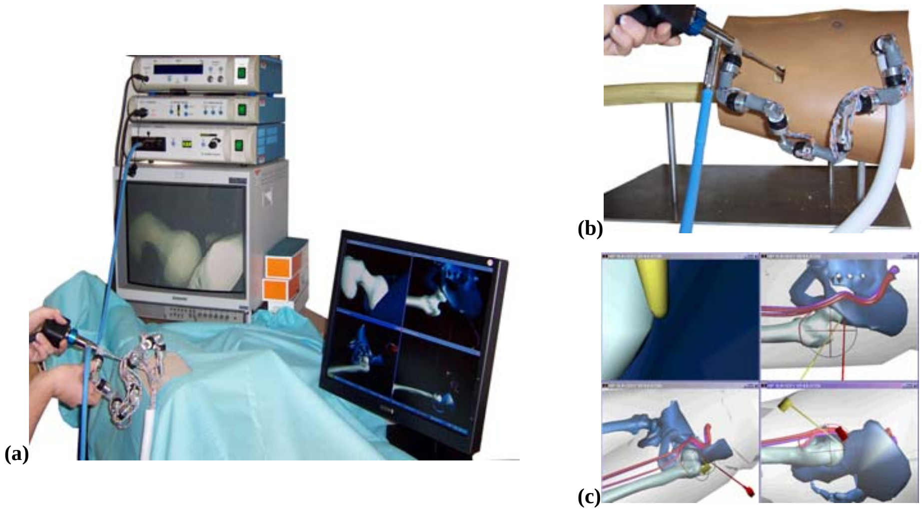


Fig. 1. Computer-aided arthroscopic hip surgery system from [8]. (a) Setup of complete computer-aided system. (b) Encoder linkage tracks an arthroscopic camera applied to a hip joint model. (c) Snapshot of computer display which shows the surgical tools and patient anatomy from multiple angles.

2. User Study Methods

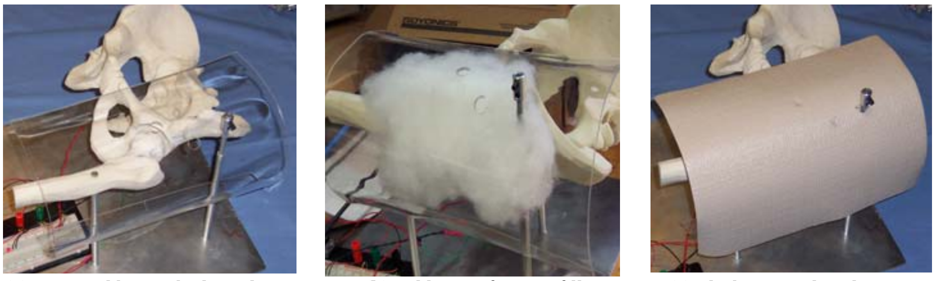
The objective of the user studies was to verify the effectiveness of the computer-aided system for hip arthroscopy by comparing user performance with and without the proposed system. Quantitatively, the time for task completion is considered as well as the tool path length. Qualitatively, feedback was obtained in the form of a survey about the participants' thoughts on the trials they performed. Specifically we hoped to determine if the computer-aided system could:

- reduce the participants task completion time,
- reduce the tool path length inside the model, and
- receive positive feedback from users about their experience.

2.1 Mockup Patient Model

A Z-Corp 3D Printer [9] rapid prototyping machine was used to create the physical hip model for the study. The generic three-dimensional models from the computer display were sent to the Z-Corp machine, resulting in identical computer and physical hip models. Two small switches were also installed on the top of the femur to mark target locations in the user study. One was placed on the ball of the femur and the other was placed near the femur neck.

To complete the hip joint mock-up, “skin” and “tissue” were included. A clear plastic cover was placed over the joint, with holes drilled for the portal incisions. Cotton fill was then added between the joint and the plastic. Without this simulated tissue, a user has an unrealistically clear view of the hip joint upon entry of the portal. The cotton fill provided a flexible and penetrable layer which would obscure view of the target until the camera was close to the target location. Over the clear support, a thin layer of flesh colored material prevented the user from directly seeing the hip joint. The hip joint model is shown in Fig. 2.



(a) Mounted hip with clear plastic cover | **(b)** Addition of cotton fill representing tissue | **(c)** Flesh cover placed over clear plastic

Fig. 2. Creation of a realistic hip joint model. Addition of tissue and “flesh” covering prevent users from viewing the targets before the camera reaches them. This is similar to an actual surgical setting.

2.1. User Study Task and Participants

The task for the user study was to use the arthroscopic camera attached to the encoder linkage to find and display the two targets on the femur. For each participant, time and path data was collected. The time from portal entry until after both targets were displayed was recorded as the time for task completion. The three-dimensional coordinates of the tool tip were recoded each time the tool position was updated on the computer display, or approximately 13 times per second. The data points are connected with line segments to estimate the user’s tool path length.

Ten participants were broken into two even groups, with each participant completing two different trials. Group I first performed the task without the computer-aided system, and then performed the task a second time with the computer-aided system. Group II completed the tasks in the opposite order: with the system first, and without the system second. The participants were split into two groups because it is possible that a user could perform better on a second trial due to the experience gained on the first attempt. All participants were engineering graduate students who were inexperienced with the arthroscopic camera.

Prior to starting the task each individual was given:

(1) oral instructions,
(2) two-dimensional visual aides, and
(3) practice time with the arthroscope on a separate hip model.

Oral instructions explained the participant’s goal to find and display the targets on the femur. Two-dimensional images of the hip joint and targets were provided, including color pictures from the arthroscopic camera of the targets. These were given as a reference for the participant before and during their trial. Finally, before starting the task, each user was given time to practice with the arthroscopic camera on a separate hip model. This allowed each user to become familiar with the viewing angle of the camera, as well as the geometry of the joint.

3. Results

The time for task completion was significantly reduced with the computer-aided system as shown in Table 1. The time for task completion varied significantly between users. However, it can be noted that except for one participant, all users from both groups were able to perform the task more quickly with the addition of the computer-aided system. The average time for task completion was 51.1 seconds with the system and 106.2 seconds without the system. The average time reduction with the computer-aided arthroscopic system was 38% across all users from both groups.

The motion of the camera inside the hip model, or the camera path length, was also reduced with the addition of the computer-aided system as shown in Table 2. With the help of the computer-aided system, the average path length was 55.0cm (21.7in). This compares to a path length of 281.2cm (110.7in) without the added visual input from the system. The tool path length within the hip joint was on average 71.8 % greater when only the arthroscopic camera images were available.

Finally, qualitative feedback from a written survey at the conclusion of the trials provided information about the benefits of the system. A near universal observation was that the computer display provided valuable feedback about the relative potion of the tool relative to the target location of the tool. Users were able to note positive and negative progress toward their goal position instead of relying on the more “trial and error” approach used without the additional system. Also, it was noted that the chain was not overly cumbersome given the small motions required inside the joint.

4. Discussion

The achieved goals of reducing task completion time, decreasing tool path length, and obtaining positive feedback have implications for an actual surgical setting. If an overall time reduction of the 38% is achieved for the tasks completed durning surgery, the savings for the patient and medical institution are significant.

Decreasing the motion of the tool within the body can be associated with decreasing the amount of tissue damage and increasing patient safety. The less the surgeon must probe around the joint and surrounding tissue, the less the muscle and connective tissue is damaged. Also, this decreases the chance that the tool moves out of a safe operating region and causes harm to a critical neurovascular structure.

While many positive comments were obtained about the computer-aided system, there are areas of improvement. For example, most users primarily used one window of the computer display to guide their motion. Future work will consider the best way to integrate multiple views along with the image from the arthroscopic camera. Also, this initial study was conducted with a group of participants who were inexperienced with arthroscopy. It would be valuable to obtain input from more experienced arthroscopic surgeons or medical students currently training for this procedure.

Table 1. User Time Performance Results

User Number		Time Without System (s)	Time With System (s)	Time Reduction (%)
Group I	1	40.0	33.8	15.5
	2	40.2	19.3	52.1
	3	53.6	41.7	22.3
	4	136.3	19.0	86.1
	5	65.5	36.3	44.6
Group II	6	116.1	46.6	59.9
	7	47.6	74.0	-55.6
	8	245.0	147.4	39.9
	9	226.6	33.7	85.1
	10	91.1	59.5	34.7
Overall Average		**106.2**	**51.1**	**38.4**

Table 2. User Path Length Performance Results

User Number		Distance Without System (cm)	Distance With System (cm)	Path Length Reduction (%)
Group I	1	235.2	23.4	90.1
	2	117.4	66.8	43.1
	3	720.9	172.0	76.1
	4	732.7	49.2	93.3
	5	159.9	48.5	69.7
Group II	6	87.0	42.6	51.1
	7	91.1	23.8	73.9
	8	133.9	55.4	58.6
	9	400.0	27.9	93.0
	10	133.8	40.7	69.6
Overall Average		**281.2**	**55.0**	**71.8**

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