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ORGINAL ARTICLE

A study of user performance employing a computer-aided navigation system for arthroscopic hip surgery

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Abstract
Object Computer-aided technology can decrease the difficulty associated with arthroscopic hip surgery. Our computer-aided system helps to navigate in the hip joint during arthroscopy by (1) tracking tool position with a linkage of encoders, and (2) using 3D computer graphics to indicate 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 as a part of continued work on this project.
Materials and methods A user study was completed to determine if the computer-aided system could help reduce task completion time and tool-path length. The time and path length provide a measure of operation time and potential tissue damage, respectively. Ten participants completed a simple navigation task with and without the assistance of the computer-aided system.
Results A time reduction of 38% and a path length decrease of 72% were achieved with the computer-aided system, confirming its effectiveness. A user survey provided overall positive feedback regarding the system. The survey information also suggested areas of improvement for continued research.
Conclusion The proposed computer-aided system can be used to address the challenges of arthroscopic hip surgery by reducing operation time and improving patient safety.

Keywords Arthroscopic surgery · Hip joint · Computer-aided surgery · Minimally invasive surgical procedure

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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. These challenges make it difficult for a surgeon to find the location in the patient body that corresponds to the target area from X-rays prior to surgery.

While several computer-aided systems for arthroscopy have been developed in recent years, the majority of these systems have been developed for knee arthroscopy. Many of these systems focus on the creation of a knee training system for doctors and medical students that are inexperienced in arthroscopy. Other systems aid a surgeon by increasing visual feedback during an actual knee procedure through the use of computerized planning or virtual models.

Systems like the knee arthroscopy simulators of Heng et al., Zhang et al., and Gibson et al., are examples of training type systems [4–6]. These systems aim to replace the use of cadavers and animal specimens in providing opportunities to practice realistic arthroscopic knee procedures. All three of these systems consist of a computer display and a workstation with permanently mounted "tools". These tools can not be removed from the workstation and have limited motion. Based on the tool manipulation, the user receives visual and haptic feedback, simulating an actual surgery. While these systems can provide some training for knee arthroscopy, they do not provide any direct assistance during a procedure.

The second and smaller group of systems, such as that by Dario et al. [7], has been developed to aid surgeons during knee surgery. In Dario's system, a new arthroscopic tool with a steerable tip and contact sensors provides a surgeon with a more dexterous operating tool. The system also provides computer-generated images during surgery using an optical position-tracking system for obtaining position information. Optical tracking systems are expensive and can have problems when an object blocks the line of sight between a sensor and receiver.

Our computer-aided solution to the challenges particular to hip arthroscopy has been developed using a novel encoder linkage for position tracking [8]. The linkage attaches to a surgical tool and tracks its location relative to the patient anatomy. Then, the position information from the linkage is used to generate a real-time display of the tools and 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. The images allow the surgeon to navigate the tool from outside the patient to within the hip joint. Then, once inside the joint and the target is within sight of the arthroscopic camera, the procedure is straightforward.

This paper discusses the effectiveness of our developed computer-aided navigation system as determined through the use of a user study 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, and
- receive positive feedback from users about their experience.

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.

Materials and methods

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 system can be found in [8].

The goal of the 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. Figure 1 shows the completed prototype system from [8].

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 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.

The encoder chain was created as a hyper-redundant linkage with eight degrees of freedom to ensure minimal interference to the surgeon from the chain. While a chain with only six degrees of freedom can reach all desired positions and orientations within its workspace, the chain has only one configuration for each target position and orientation and that configuration may encroach on the surgeon's workspace in some cases. The current linkage 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. Rotational encoders at each joint location capture the tool motion relative to the patient anatomy.

The main parts of the linkage, as diagramed in Fig. 2, are the US Digital E4 encoders [10], the bearings, and encasement parts for the bearings. The encoder diameter is 2.16 cm (0.85 in.) with a resolution of 300 counts per revolution. The bearings allow the relative rotation between links as measured by the encoders. The inner races of the bearings are attached to one link, while the outer races connect to the next link in the sequence. Finally, a 90° bend in the attachment between links place adjoining axes of rotation perpendicular to one another.

For the computer display, a three-dimensional model of the patient's hip joint must be created prior to surgery. The model can be obtained from computerized tomography, magnetic resonance imaging, or a recently developed method using X-ray images to create the patient specific model [11].

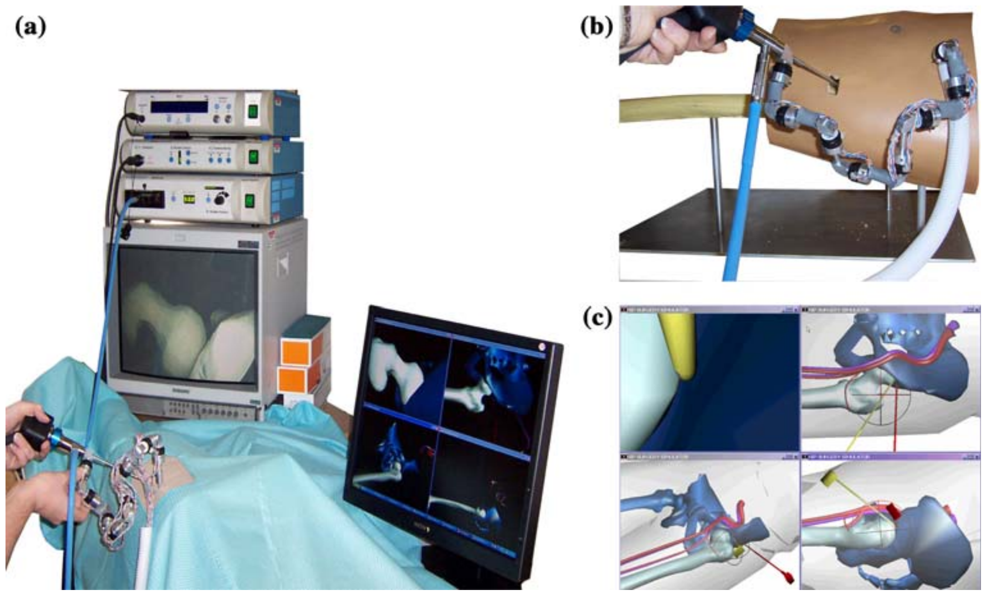

Fig. 1 Computer-aided arthroscopic hip surgery system from [8]. **a** Setup of complete computer-aided system with Smith and Nephew arthroscopic equipment [9]. **b** Encoder linkage tracks an arthroscopic camera applied to a hip joint model. **c** Snapshot of computer display which shows the surgical tools and patient anatomy from multiple angles

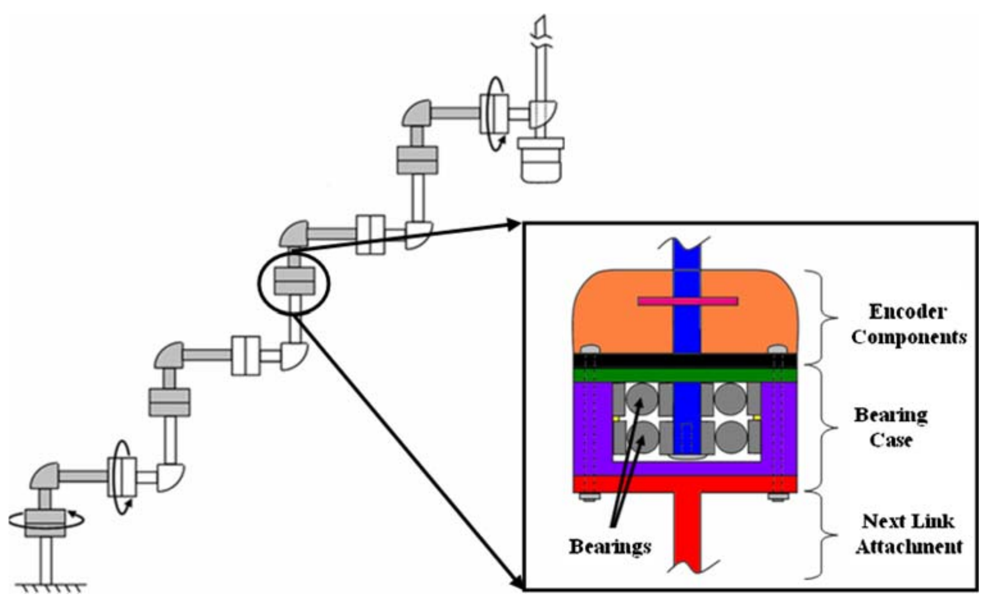

Fig. 2 Cross-sectional diagram of the main components of a link of the encoder linkage

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. During current hip arthroscopy, the patient's feet are placed into fixtures and a padded post is placed between the patient's legs. A force is applied to the patient's feet to create work space between the pelvis and ball of the femur. As a result of this force and positioning method, we have assumed that there is little relative motion between the pelvis and femur. Therefore, in our system the base pin is located in the pelvis and the assumption has been made that the femur has no relative motion. Future work must consider the accuracy of this assumption.

Given the patient model and operative tool positions from the encoder 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. 1c display the hip joint from multiple angles for the surgeon. The upper left window is a computer generated version of the view from

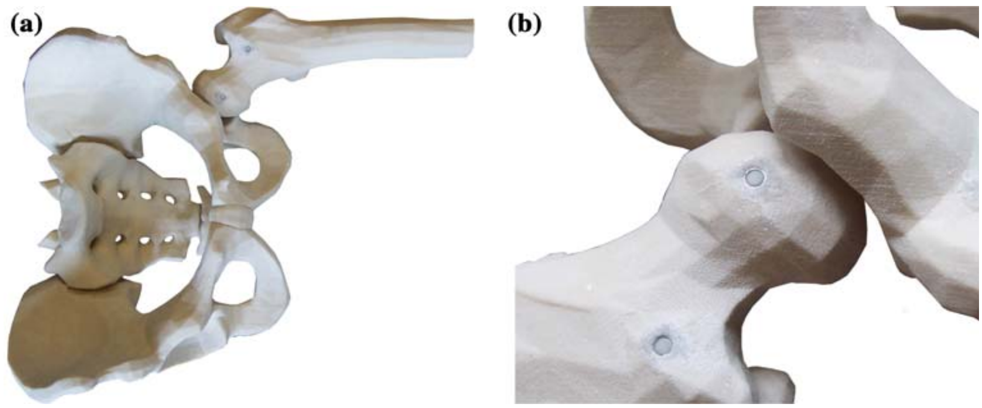

Fig. 3 Rapid prototyped model of hip joint. **a** Full view of pelvis and femur models. **b** Close-up view of user study targets on femur

the actual arthroscope. The remaining three windows can be adjusted to show the hip from any desired angle.

An important consideration is the linkage accuracy. Initial testing of the linkage precision was performed and complete results are presented in [8]. The global position error was 5.29 mm with a standard deviation 0.82 mmm. However, when the initialization error was removed, and only the linkage precision was tested, the position error was 0.75 mm with a standard deviation of 0.55 mm. Current work on the linkage involves lowering the system error though the application of numerical techniques.

Mockup hip model for the user study

For this initial study, we have created a mockup of the hip joint to represent our "patient". A computer model was used to rapid-prototype an exact match in the physical model. Note however, when the system is in actual use, the computer model would be generated from the patient as discussed in a previous section. We have chosen not to obtain a computer model from the patient model since this conversion does not create a perfect match. By eliminating this source of variability, it is possible to concentrate on the effectiveness of the developed system on navigation performance. In future work, a cadaver can provide a more accurate user experience, with the option to move from patient to computer model.

The Z-Corp 3D Printer [12] rapid prototyping machine was used to create the physical hip model for the study. The same three-dimensional model is also used for the computer display, 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. The target on the ball of the femur represents the approximate location a surgeon could need to fix irregularities in the surface. If an irregularity exists in the ball, it could cause joint pain during hip motion. The second target is a possible location for the surgeon to reach to resolve a joint impingement issue. If extra bone exists on the neck of the femur, it could prevent full joint rotation without contact between the femur and pelvis. The pelvis and femur models are shown in Fig. 3.

To complete the hip joint mock-up, "skin" and "soft 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 soft 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., similar to the visual obstruction of the soft tissue and hip capsule. Over the clear support, a thin layer of flesh colored material prevented the user from directly seeing the hip joint. See Fig. 4.

Task and participants of the user study

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 shown in Fig. 3. For each participant, time and path data was collected. The time from portal entry until after both targets were found 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

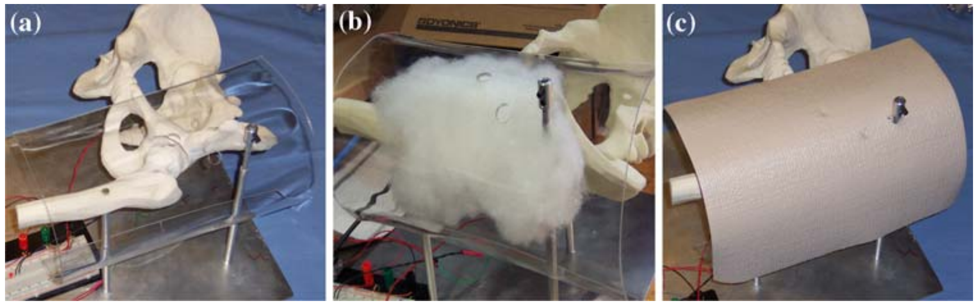

Fig. 4 Creation of a realistic hip joint model. Addition of tissue and "flesh" covering prevent users from viewing the targets before the camera reaches them. This is similar to an actual surgical setting. **a** Mounted hip with clear plastic cover; **b** addition of cotton fill representing soft tissue; **c** flesh cover placed over clear plastic

possible that a user could perform better on the second trial due to the experience gained on the first attempt. By varying the order for the trial with the computer-aided system we can account for the possible bias on the second trail. All participants were engineering graduate students who were inexperienced with the arthroscopic camera. Nine of the participants were male, one was female.

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. The two-dimensional images of the hip joint and targets from Figs. 3 and 5 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. Included in these pictures was Fig. 5d which demonstrated the goal image for the participants. The circular target was approximately centered on the screen and approximately the size of a third of the screen length. 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. These visual aides represent the same information that a doctor would have prior to surgery. For example, they would have a two-dimensional X-ray with a target location determined, then during surgery they would need to find that location in the patient with no three-dimensional feedback.

Results

The time for task completion was significantly reduced with the computer-aided system as shown in Table 1. Although the time for task completion varied significantly between users, with the exception of one participant, all users from both groups were able to perform the task more quickly with the addition of the computer-aided system. One user in Group II had difficulties penetrating the tissue on the first trial, resulting in a longer time trial with the computer system. The average time for task completion was 51.1 s with the system and 106.2 s without the system. The average time reduction for all users in both groups was 38% with the computer-aided arthroscopic system.

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 55.0 cm (21.7 in.). This compares to a path length of 281.2 cm (110.7 in.) without the system. The tool path length within the hip joint was on average 71.8% greater when only the arthroscopic camera images were available.

In addition to the numerical data, a visual comparison of the tool path with and without the computer-aided system demonstrates the improved performance with our system. Figure 6 shows two-dimensional plots from three participants' data sets. The plots are superimposed over a picture of the hip joint to provide better context for the graphs. A range of path-length values were selected. Figure 6a, b is an example of a user with a very large improvement. Figure 6c, d show a participant who had an average amount of improvement. Finally, Fig. 6e, f are from a participant that had a smaller amount of improvement. In all cases, the tool path with the computer-aided system follows a more direct route to the desired targets. Without the computer-aided system, the tool path is longer and the tool moves unnecessarily into extraneous tissue regions.

Finally, qualitative feedback from a written survey at the conclusion of the trials provided information about the benefits of the system. Participants felt 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 computer-aided system. Also, it was noted that the chain was not overly cumbersome given the small motions required inside the joint.

Discussion

In this work, we determined that our computer-aided navigation system:

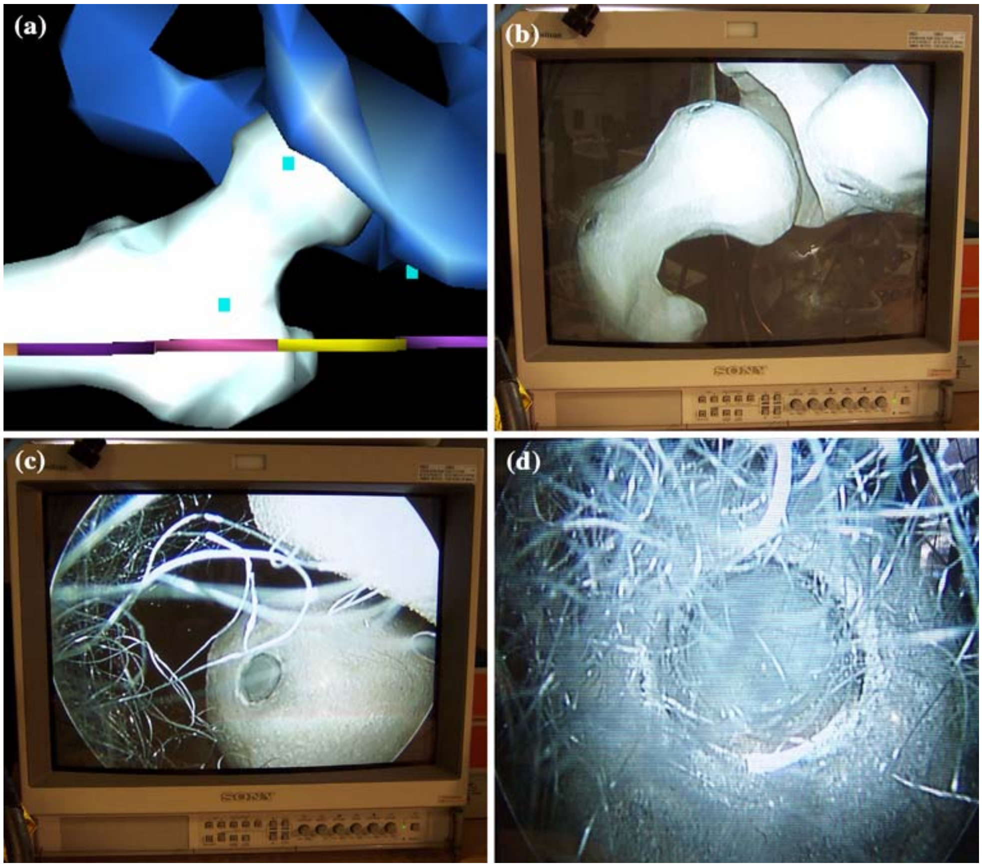

Fig. 5 Two-dimensional images provided for participants. **a** Computer-generated view of targets, **b** view of hip model from just inside the portal incision, without soft tissue, **c** view approaching targets with soft tissue, and **d** example of the desired image of a target

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

- reduced the participants task completion time by 38%,
- reduced the tool-path length by 72%, and
- received positive feedback.

The achieved goals of reducing task completion time, decreasing tool-path length, and obtaining positive feedback have implications for an actual surgical setting.

The time reduction seen in this user study was on the order of a minute. While this initially appears to be a small time savings, this savings is multiplied by the number of tasks that must be completed during the surgery. Ideally, if an overall time reduction of the 38% is achieved for the entire surgery, the savings for the patient and medical institution are significant. It must be noted however, that

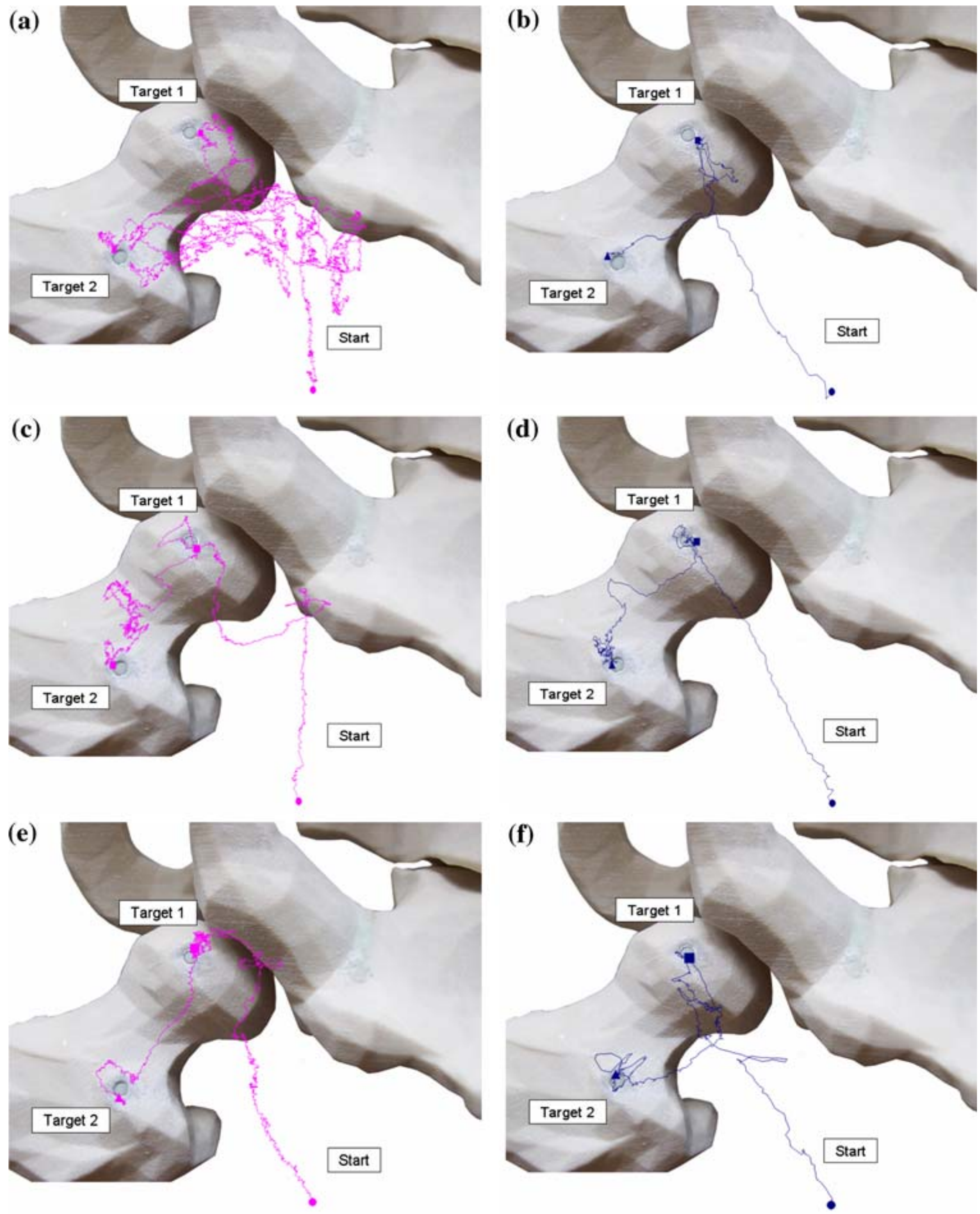

Fig. 6 Comparison of a user's tool path with and without the computer-aided system. Users with a range of path-length reduction values were sampled. Users were instructed to move from the starting position to Target 1, then to Target 2. **a** Tool path of user number 9 without system; **b** tool path of user number 9 with system: 93% path-length reduction; **c** tool path of user number 10 without system; **d** tool path of user number 10 with system: 70% path-length reduction; **e** tool path of user number 6 without system; **f** tool path of user number 6 with system: 51% path-length reduction

some additional time will be added to the procedure for the system setup. Also, general surgery steps such a patient preparation and cleaning up after the procedure will not have a time reduction as a result of using this system.

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. As demonstrated with Fig. 6, the tool path is smaller and remains within a smaller working envelope with the computer-aided system.

Another important point is that although Group I and Group II completed the trials with and with out the system in a different order, the same results were obtained. Both groups observed an improvement in task completion time and tool path length when using the computer-aided system. One would normally expect a better performance on the second trial, due to increased familiarity with the target locations in the earlier trail. However, all the participants in Group II performed better on their first trial than their second trial, due to the computer-aided system.

Several interesting observations were made during the participant trials. First, when a user performed a trial without the system, a large pause in tool motion was noted upon entering the portal. It appeared that the users were unsure of how to best start their search for the target. This pause was not readily detected with the computer-aided system. The images from the computer-aided system provided an instant plan for the participants with feedback on positive or negative progress. A second observation is that users often displayed a portion of the target without realizing it when not using the system. Reaching the target most often came as a surprise to the participant. They would display all or part of the target, but pass by it because they were not expecting its appearance. When using the system, participants knew they were approaching a target, so we generally prepared to stop the camera over the target.

Finally, positive feedback was desired about the overall user experience. Surgeons do not want an overly complicated or cumbersome device in the operating room. Users found that the system provided valuable feedback without significant drawbacks. This increases the probability that surgeons will use this system for arthroscopy.

While many positive comments were obtained about the computer-aided system, there are areas of potential improvement. For example, most users responded in the survey that they primarily used one window of the computer display to guide their motion. It was difficult to simultaneously consider multiple views. Future work will consider the best way to integrate multiple views along with the image from the arthroscopic camera.

This initial study was conducted with a group of participants who were inexperienced with arthroscopy. This would be similar to training new doctors for an arthroscopic procedure. However, it would be valuable to obtain input from more experienced arthroscopic surgeons or medical students currently training for this procedure as well.

The proposed computer-aided system for arthroscopy can be used as a tool to address the challenges of joint navigation in arthroscopic hip surgery. The system will supplement the limiting view from the arthroscope by tracking surgical tools with a linkage of encoders and creating an additional display of patient anatomy. The effectiveness of this system was verified though a user-study of a simple navigation task. When provided the additional visual feedback of our system, participants were able to perform the task more quickly and navigated with a safer and more efficient tool path.

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