Design and Evaluation of 3-D Pre-operative Planning Software: Application to Acetabular Implant Alignment

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Abstract

We describe a methodology for evaluating the user interface components of a pre-operative planning system for performing complex 3-D spatial manipulation and reasoning tasks. The design of a pre-operative planning system for the alignment of acetabular implants in total hip replacement (THR) surgery is used as an example. For this application, we have implemented several alternatives to two of the planner's sub-systems. We report the results of a pilot study which evaluate these alternative components with respect to task and user specific design criteria.

Keywords: computer-assisted orthopaedic surgery, pre-operative planning, total hip replacement surgery.

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1. Introduction

An important aspect of any software system is presenting the user with a good interface. If the user interface is poor the system runs the risk that it will not be used, or worse, it will be used improperly with potentially harmful results. This is especially true for pre-operative planning software, for which the results of the plan can directly impact the outcome of a surgical procedure.

While there are many “rules of thumb” for good user interface design, there are many aspects of the design which are unique to the particular system being built. Design requirements are driven not only by the task to be performed, but by the expertise and experience of the potential system users. User attributes which the interface design process must address include [1]:

- the user’s level of computer sophistication
- the user’s domain knowledge
- how long a user is willing to spend learning the software
- how long a user is willing to spend using the software

We have structured the design of a pre-operative planning system into two phases: design of individual components, and integration of the components into a complete system. During the design process, there may be multiple components capable of satisfying a particular design requirement. Evaluation methods may be useful for selecting among competing components. In this work, we have developed techniques for evaluating components of a pre-operative planner with respect to criteria which measure component effectiveness for solving the task. Incrementally evaluating the system components early and continuously throughout the design cycle ensures that the final system both meets the task requirements and is acceptable to the user.

The type of pre-operative planning systems which we are building must allow the user to perceive, reason about, and manipulate 3-D representations of anatomical and artificial objects. There are two fundamental components of such a planner: an *output interface* and an *input interface*. The output interface communicates all necessary information regarding the state of the planning process to the user. For example, in an orthopaedic planning task the state may be the position and orientation of a surgical implant relative to a representation of patient anatomy. For such a task, several output interface methods are possible, including:

- multiple cross sectional views of CT or MRI images superimposed with overlays of an implant’s cross section
- 3-D rendered surface models of the relevant anatomy and implants

- stereoscopic views of 3-D rendered surface models
- volumetric renderings of the anatomy and implant

The choice of output interface method is important because it is the primary source of feedback to the user on the state of the plan. Some methods may be superior to others not because they present more information, but because they present the information in a format that is more comprehensible to the user. For example, views of the anatomy aligned in orientations which are familiar to a surgeon may facilitate spatial reasoning about the task. The interface must be careful not to overload the user with too much information, which could lead to important information being ignored or misinterpreted.

The primary purpose of the input interface is to provide a mechanism which allows the user to manipulate the state of the 3-D planning environment. Of necessity, there is a tight coupling between the input and output interfaces. There are many input interface methods which are possible, including:

- simple textual input
- mouse manipulated buttons, dials or slider widgets
- direct 2-D interaction using a mouse (e.g., to modify the state of a graphical object representation)
- direct 3-D interaction using a device such as a spaceball or data glove

In addition to choosing a physical input device, the design must appropriately map device outputs into logical actions which modify the planner state, and which are communicated back to the user via the output interface.

Selection of appropriate output and input interface methods should be based upon task and user requirements. The criteria used to evaluate these methods may include: system responsiveness, the speed and/or accuracy with which the user can accomplish the task, the level of fatigue or frustration induced by the interface, and the cost of implementation.

We have developed evaluation techniques for comparing user interface output and input methods with respect to task and user specific criteria. We are using these techniques as an integral part of the design process of an acetabular implant pre-operative planner; however, the concepts are general enough to be applied to any system which requires complex user interaction with a 3-D planning environment.

2. Materials and Methods

One step in total hip replacement surgery is the insertion of the acetabular implant. During surgery, the pelvic bone is reamed with a cutter to match the hemispherical shape of the implant exterior. The implant is then pressed into the bone at an orientation which will allow a full range of leg motion. Proper alignment of the acetabular component with respect to the patient's pelvis is crucial in reducing the risk of post-operative implant dislocation.

Our group has developed the HipNav intra-operative navigational guidance system to assist the surgeon in proper alignment of the acetabular implant [2]. One of the inputs required by the HipNav system is a pre-operatively generated plan of desired implant alignment based upon CT images of the hip. The primary function of the pre-operative planning software is to allow the user (i.e., surgeon) to perform the complex 3-D reasoning and manipulation required to align the implant with respect to the patient's anatomy. Currently, determination of desired alignment is based solely upon user reasoning. Ongoing development of the planner will: incorporate planning of femoral implant placement; provide an interface to a 3-D kinematic range of motion simulator [3]; and provide interfaces to various other biomechanical simulations [4]. Each of these components will provide additional information for generating optimal acetabular implant alignment plans.

Traditional pre-operative planning for total hip replacement, if performed at all, consists of the surgeon sliding properly scaled acetate overlays of implant cross sections over patient X-ray films on a light table. The purpose of this procedure is not to determine the position of the implant, but to simply identify a range of implant sizes that may be required during surgery. Computer assisted intra-operative guidance systems such as HipNav, however, require pre-operative plans which specify not only implant size, but also desired position and orientation.

The acetabular implant planning task can be divided in to three sub-tasks:

- choosing the proper implant exterior diameter to maximize bone contact in the patient's pelvic cup,
- locating the implant's center of rotation, and
- orientating the implant within the acetabulum.

Acetabular implant orientation is often specified in terms of two angles relative to the patient anatomy, abduction and anteversion. These angles specify rotations which transform the implant from a neutral position to the desired position (since the implants we are currently using are symmetric about their central axis, a third angle is not required).

The planning software must allow these three sub-tasks to be performed accurately and efficiently. Although they could be controlled through one monolithic interface, an early design decision was to separate the later two sub-tasks to simplify user interaction and implementation. Thus, the planning task can be divided into two phases: 1) sizing and positioning the implant, and 2) orienting it. The user can switch back and forth between the two phases.

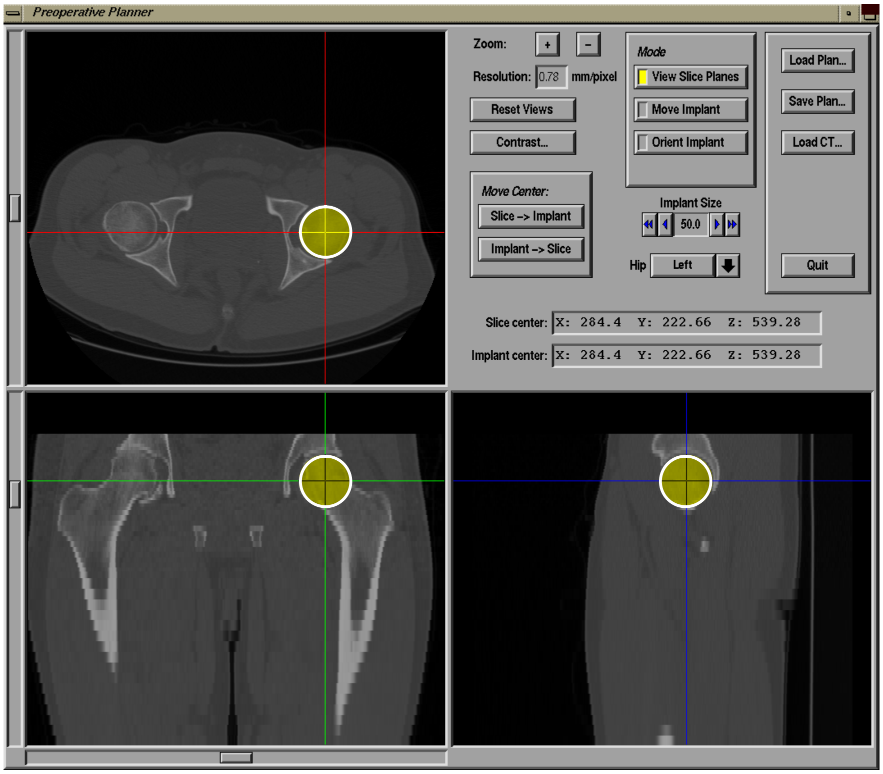

Figure 1. CT cross section output method for positioning the center of rotation. Moving the mouse in one view updates the cross sections in the other views. The implant is represented as a sphere.

2.1. Output Interface Methods

Output from the planner to the user takes place entirely on a two-dimensional computer graphics workstation monitor. In the first planning phase, the surgeon can manipulate the size and position of the implant and examine how the exterior shell of the implant intersects the bone in the CT data. The planner displays multiple 2-D cross sections through the CT data, with a graphical overlay of a cross section of the implant. Since the orientation of the implant has not been specified at this time, it is represented as a sphere, and the cross sections as circles, as shown in Figure 1.

In the orientation phase of planning, the user is presented with a 3-D surface model of the pelvis and a 3-D representation of the implant, as shown in Figure 2. The implant is modeled as a hemisphere with an arrow pointing along its central axis. The models can be zoomed and rotated for examination from any point of view.

For the purposes of this study, these two output interface methods are the only ones used. We are experimenting with three-dimensional displays [5], and several other output interfaces, and will incorporate these into our evaluation in the future.

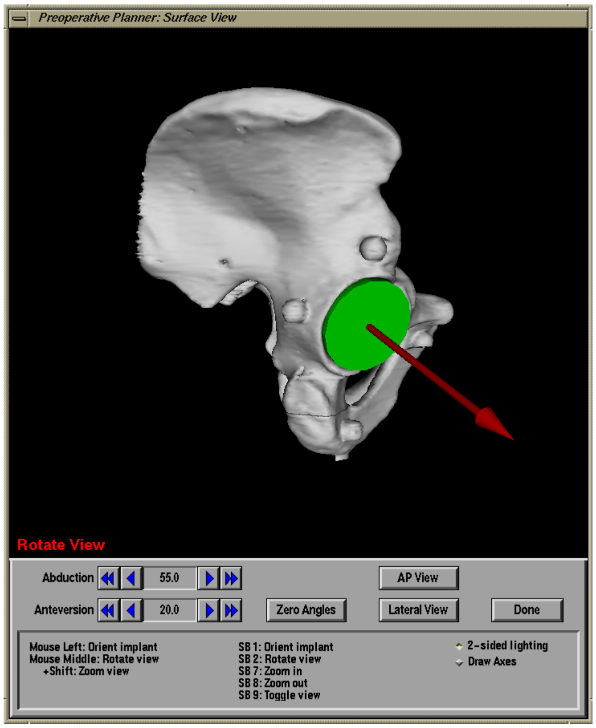

Figure 2. Surface view output method for orienting the implant. Implant can be rotated either by changing abduction and anteversion angles, by manipulating directly with the mouse, or by manipulating with the spaceball. This particular surface model shows the fiducial balls used for registration in the user test.

2.2. Input Interface Methods

We are evaluating three input interface methods for the planner: graphical buttons on the display which the user can click to change implant orientation; direct 2-D mouse manipulation of objects on the display, and 3-D spaceball manipulation of objects on the display. The spaceball is a 6 degree-of-freedom input device. The user grasps an 8 cm diameter sphere. Pulling and twisting actions are measured by force and torque sensors and are translated in to cartesian translations and rotations by the software.

Implant size can be selected via buttons, with the new size reflected by the graphical overlay. The 3-D position of the implant can be moved by clicking on the implant in one of the three views and dragging it with the mouse. The implant moves within that 2-D plane, with the corresponding position and CT cross sections continuously updated in the other two views, as seen in Figure 1. In a second input mode, the user can manipulate the implant and slice positions in 3-D with the spaceball, with the three views updated relative to the spaceball translation elements. The user can also change the orthogonal CT slice plane orientations to view implant-bone intersection at any location.

For the orientation phase, we are evaluating button, mouse and spaceball methods of input. In the button only mode the user can switch between anterior-posterior (AP) and lateral views, and enter the abduction and anteversion angles. The results are instantly updated on the surface view of Figure 2. In the mouse manipulation mode the user can click and drag on the surface model. This motion is converted to a corresponding rotation of either the viewing direction or the implant orientation, depending on the mouse button. The mapping between mouse motion and rotation is very intuitive. The spaceball mode is similar, except the user applies twisting motions to the spaceball which are mapped to changes in either viewpoint or implant orientation.

2.3. Evaluation Methodology

Several techniques have been used to evaluate which input and output methods are better suited to the planning task. These techniques are general, and can be applied to similar design tasks.

2.3.1. User Group Identification

The first step in the evaluation process was to determine the target users of the system. For the acetabular implant planner this group includes surgeons and other clinicians who can interpret CT data and who understand the requirements of THR surgery, but are not necessarily expert computer users. This group is labeled “domain experts.” Unfortunately, access to surgeons (and especially their time) is limited. To get meaningful statistics on usability it is desirable to have a large number of subjects use the system over time. It has been shown that testing interfaces on users who are familiar with the domain, but not experts can still yield useful results [1]. To this end we identified a second user group, “computer experts,” who are familiar with computers and interfaces and understand the concept of CT data, but are not familiar with the requirements for THR surgery. Computer experts were recruited from the university community, and thus are more accessible and plentiful.

2.3.2. Talk Aloud Sessions

Once user groups had been identified, we conducted informal usability sessions with the domain experts utilizing a “talk aloud” protocol. In these sessions we asked the experts to use a version of the planning software to perform an acetabular implant alignment task using real patient data. As they used the system, the experts were encouraged to talk through what they were doing and why (doctors tend to be very good at talk aloud tasks – it is similar to the way they teach medical procedures). From these sessions a number of improvements to the interface were identified and implemented.

2.3.3. Usability Experiment

The next step in the evaluation was to conduct a pilot usability experiment [6] using the computer expert group. In this experiment, 12 people used the planner with the various combinations of output and input interface methods to perform a task for which there was a measurably correct answer. During the experiment, position and orientation errors between the user’s plan and the correct result were recorded at 2 second intervals. Total planning time and final placement errors were also recorded. Minimum tolerable error thresholds were

Figure 3. Pelvis phantom with implant used as model in usability experiment. Note fiducial spheres.

established so the task could not be completed until the error was within a specified bounds.

An ideal experimental task would exactly mimic the real application of the software. For the planner, such a task would be to have surgeons plan “optimal” acetabular implant position and orientation based upon CT data from a real patient. Unfortunately, this task does not have a “correct” answer, and each surgeon will have his own opinion regarding optimal implant placement based on his experience.

Therefore, a substitute experimental task was designed. This task used a phantom pelvis with spherical fiducial markers attached (Figure 3). An implant was placed in the right acetabulum, and its position was measured with respect to the fiducials in order to accurately determine the actual implant placement. This “true” implant placement was then related to the CT coordinate system using a simple point-based registration method and the attached fiducial markers. CT scans of this phantom, and a surface model built from the scans were input to the planner. The phantom and implant were given to the test subject who was asked to use the planning software to recreate the actual implant position and orientation using one of the interface methods. The structure of this experiment is illustrated in Figure 4.

Although the experimental task does not exactly map to the real task to be performed by the planner, it does exercise and evaluate the 3-D visualization and manipulation interfaces of the planner, which are key portions of its functionality. Since the users perform identical tasks using different interface methods, the methods can be compared with respect to the evaluation criteria. Thus, this experiment is not evaluating the usability of the software for acetabular planning, but rather it is comparing various functional components which are required for general 3-D planning tasks.

Each subject performed three experiments. Prior to the experiments the subject was read a script which explained the task and how to use the software. Using the same script for each subject helped ensure that the tester did not influence the results by getting better at explaining the task over time. Each experiment began with the user positioning the center of rota-

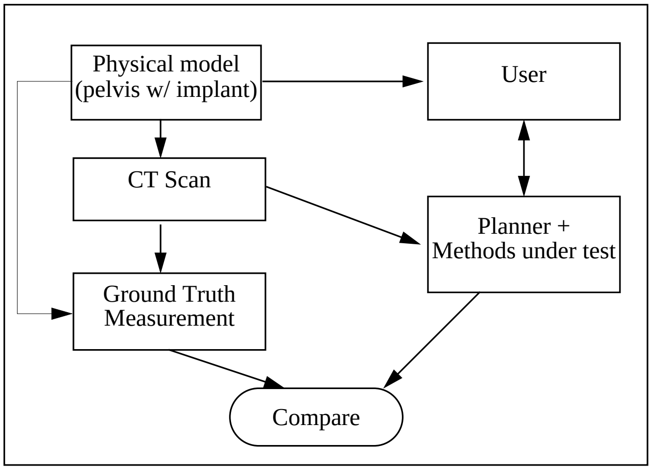

Figure 4. Structure of usability experiment.

tion of the implant using the orthogonal view output method and the mouse manipulation input method (spaceball positioning was already shown to be too difficult for this task). Upon successful completion, the orientation phase was entered using the surface view output method with the three different input methods: button, mouse manipulation, and spaceball manipulation. After the experiments, subjects were asked for their preferences and suggestions for the various methods.

3. Results

The results of the talk aloud sessions with the domain experts proved to be most useful. A number of problems were identified and enhancements suggested. These included the ability to “dial in” abduction and anteversion angles (e.g., to nominal orientations), and buttons to display the AP and lateral views which are already familiar to surgeons. These improvements were implemented immediately. Another suggestion was to add a means of visualizing the intersected volume between implant and bone. We are currently implementing and testing visualizations which provide this capability, including radial 2-D CT slices about the implant’s central axis, and volume rendering with varying degrees of transparency.

We tried using the spaceball for the implant and slice positioning task in the orthogonal slice view method using only the three translation elements, but we found that users had a difficult time mapping motions on the spaceball to the three views, and became very frustrated. Further testing with this input mode for positioning was discontinued. Feedback from the users also showed that keyboard entry for fine positioning might be desirable.

12 users were recruited from the computer expert group for the pilot usability experiments. Observations of the users and their post-experiment comments indicated that the direct mouse manipulation input method was by far the easiest and most intuitive to use. The users were able to rapidly and accurately complete the positioning phase of the task, as shown in Table 1. The display resolution for the experiment was 0.75 mm/pixel. On average, the users

were able to achieve the correct position within 2 pixels (the zooming function was disabled for the experiments). This table also shows that after the first trial, the users learned how to better manipulate the interface and were able to improve their speed (the same input and output methods were used for this phase in each experiment).

Trial	Position error (mm)		Position time (sec)	
	mean	s.d.	mean	s.d
1	1.72	0.93	45.55	27.86
2	1.58	0.76	30.00	13.66
3	1.67	0.82	25.09	10.58

Table 1. Results of positioning phase of experiment.

In the orientation phase, the computer expert group found the abduction/anteversion angle buttons coupled with AP/lateral view display difficult to use because they had trouble internally mapping the angles to expected actions. The domain experts, on the other hand, were very comfortable with this method. Users who had previous experience with the spaceball found it easy to use, but others had a hard time mapping and controlling its motions, tending to overshoot their intended position and oscillating back. There were no significant differences in accuracy for the three input methods, but direct mouse manipulation proved to be the fastest, as summarized in Table 2.

Input method	Orientation error (deg)		Orientation time (sec)	
	mean	s.d.	mean	s.d.
Buttons	5.57	3.02	150.45	115.93
Mouse	4.94	2.66	88.64	38.88
Spaceball	5.27	2.19	174.73	79.63

Table 2. Results of orientation phase of experiment.

One aspect of usability which the experiments did not take in to account was learning by the subjects. Because each experiment used the exact same implant position, some of the subjects learned visual cues on what the implant should look like in the pelvis which may have aided the orientation process after the first trial. In future experiments, we will use different implant positions, or randomize the order in which the methods are used. We also believe that with practice, users would be better able to manipulate the spaceball, so repeating the experiment multiple times would be appropriate.

One subject learned a “trick” to the orientation task – holding the model pelvis so the implant was straight on, rotating the view of the pelvis so that it matched, and then positioning the implant so the arrow was pointing straight out. This yielded a very accurate orientation, but unfortunately did not test the interface in its intended mode of use. This pointed out a limitation of the experiment, but did highlight the ease of 3-D manipulation with the interface.

4. Discussion

Although our evaluation experiments were designed to test the usability of a specific type of software for a specific task, the methodology and even the results to some extent can be applied to other systems that entail 3-D planning. Direct mouse manipulation proved to be both intuitive and accurate for users. This is good from a systems standpoint, since it is both simple and cheap to implement. While the spaceball shows promise for 3-D rotational manipulation, it has a long way to go to decisively beat the mouse.

One of the most valuable exercises in our evaluation was the talk aloud sessions with the domain experts. This brought to light many expectations and preconceptions early in the design cycle, when it was easy to accommodate changes in the interface.

While the usability study with the computer expert group did not uncover any major design flaws or insights, it did validate our ideas about what would make a good interface and has allowed us to focus our attention on refinement. We are now examining other output methods (such as volume rendering) and will apply the same techniques to compare them with the previous methods. We are also preparing a more comprehensive usability study using domain experts as subjects to determine how domain and computer skills impact our design decisions.

5. Acknowledgments

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