Development of a Surgical Interface for Cryoablation of Kidney Tumors

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Abstract. Autonomous surgical systems aim to improve surgical treatments in all stages of the clinical workflow. A surgical interface should be safe, robust, and user-friendly. In this article, the functionality and usability of a surgical interface as critical factors for acceptability are investigated. Then, the surgical interface for the cryoablation of kidney tumors is designed, with consideration of the functionality and usability factors. The surgical interface includes a preoperative surgical simulator that allows the surgeon to plan the surgical interventions. The surgical interface with one surgeon is evaluated.

1 Introduction

Surgical interfaces aim to improve surgical treatments in all stages of the clinical workflow. Interfaces are used for the interpretation and quantification of the patient information, and for the presentation of an integrated workflow where all available data is combined to enable the optimal treatments possible. The use of surgical interfaces may reduce the risks involved in conventional surgical procedures. Additionally, the interfaces can help the surgeon to perform a safe and autonomous surgical operation. Thus, recently, various surgical interfaces for computer-aided surgery have been developed and commercialized.

CAScination is a well-known commercial system that integrates modern stereotactic technology, dedicated to complex liver interventions, and surgery [1]. Another surgical interface has been developed to help surgeons during cardiac surgery [2]. A preoperative surgical simulator has also been designed to allow the surgeon to plan the surgical interventions for liver surgery in the Patient-Specific Simulation and Pre-Operative Realistic Training for liver surgery (PASSPORT) project [3]. CASPER has also been designed to provide guidance information to the surgeon who performs the puncturing operation.

Surgical interfaces need to be designed with the surgeon at the center. No additional complexities should be introduced that could affect the surgeon's ability to complete the intervention successfully. Thus, the surgical interface should be designed in such a way that it will automate the targeted surgical procedure to increase both patient and the user safety. Increasing the speed of the surgical process and decreasing the level of invasiveness are therefore two important factors. These introduce new constraints to the surgical process by imposing time constraints and forcing the surgeon to operate on deeply located lesions without actually seeing or touching them. Thus, there is a need to design a surgical interface that will benefit maximally from the surgeon's skills, provide as much information as possible, and include tools to increase the surgeon's ease of use. Additionally, the surgical interface should be safe, robust, and user-friendly for the surgeon. Thus, it is important to follow a specific methodology when designing the surgical interface.

Initially, this study investigates the functionality and usability factors of the surgical interface because they are the sub-features of usefulness, which is a critical factor for the acceptability of the surgical interface. Surgeons desire to use functional and usable systems more frequently. Only, functionality-focused designs often fail to meet the usability needs. It is possible that a functional system is not usable or vice versa. Therefore, both usability and functionality are interrelated, and should be taken into account in the design processes of a surgical interface. The question of which factors, from the surgeon's perspectives, are more important than others has to be answered to satisfy the surgeon's demands. The importance of the usability and functionality factors for a surgical interface are examined using a questionnaire. Surgeons completed this questionnaire. Most of the recommendations given to the design team of the surgical interface consider the vital usability and functionality factors.

The surgical interface is commonly divided into three separate phases: preoperative, intraoperative and postoperative. Imaging, segmentation, 3D modeling, and registration tools are required for both the preoperative and intraoperative phases. The preoperative phase is usually decoupled from the surgical intervention since various possible scenarios can be simulated a priori. When a suitable plan is selected in the preoperative phase, this plan can then be put into action in the intraoperative phase. The pre-operative plan can sometimes be revised due to intraoperative phase findings, such as additional tumors detected during tumor resection. Results of the surgical procedure such as the percentage of tumor ablated are documented in the post-operative phase. In this study, we only concentrate on the preoperative surgical simulator of the surgical interface, which allows the surgeon to plan the surgical interventions before the real surgery.

Various computer languages are used to develop surgical interfaces. The telesurgical robot system, daVinci, uses a Surgical Assistant Workstation (SAW) that provides a software framework written in C++ [4]. The SAW framework is capable of integration of the patient models (i.e., preoperative images) and intraoperative imaging (i.e., ultrasound) within the video display of a telesurgical robot system. XML component-oriented architecture has also been used to develop a surgical interface [3]. This framework facilitates software prototyping and configuration in the field of image-guided surgery. It also includes visualization, tracking, and data input/output aspects. In this work, the surgical interface is developed using Microsoft Visual Studio 2010 Development Environment. The routines are written using C Sharp programming language. The visualization toolkit (VTK) is used for 3D medical image processing and visualization.

The architecture of the human-robot interaction for the puncturing task in a surgical intervention in the kidneys is presented in Section 2. The usability and functionality factors of the surgical interface are given in Section 3. Section 4 presents the design details of the surgical interface. The evaluation results of the surgical interface with one surgeon are given in Section 5. The conclusion and possible directions for future work are presented in Section 6.

2 Architecture of Human-Robot Interaction

A human–robot interaction interface is responsible for developing a communication framework in which the surgical instrument, such as a robot, can convey information to, and receive commands from, its human supervisor (the surgeon). The surgical interface is the main gateway of the surgical devices that communicates with the surgeon using available data, such as medical images, models, surgical plans etc.

The surgical interface communicates the surgeon's instructions to the controller, which is the planner. The controller is responsible for the planning and execution of the surgical action, and for the detection of the unexpected and problematic situations that might occur during the surgical operation. Surgical actions, patient (the phantom), surgical tools, and the environment are monitored and observed through the surgical interface as well. The surgical interface shows what the surgeon could not perceive visually during the surgery. The data gathered by the controller and from the other subsystems are communicated to the surgeon and the technician during the surgery. The architecture that demonstrates the interaction between the surgical interface, and the rest of the modules (medical images, sensors, robot, robot control, and physical models) is shown in Fig. 1. The different information sources, such as patient models, preoperative CT images, and ultrasound are registered to each other. This study only concentrates on the development of the surgical interface of the human–robot interaction interface.

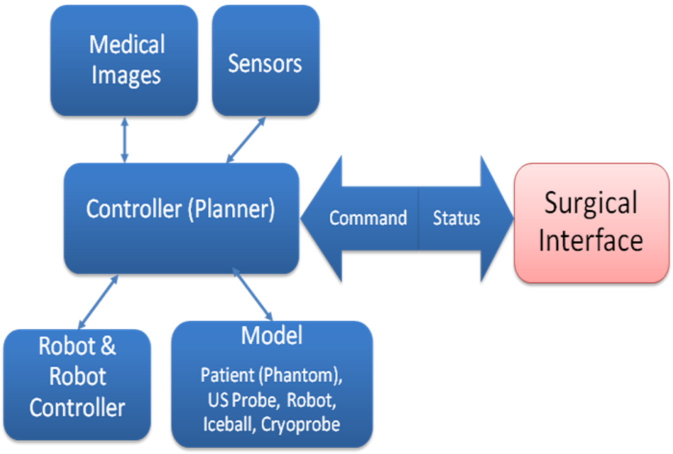

Fig. 1. Architecture of the human-robot interaction interface.

3 Usability and Functionality Factors of Surgical Interface

The factors of usability and functionality examined have been selected and classified on the basis of a literature review and the personal judgment of the experts. Usability refers to the extent to which a system facilitates users to utilize its functions easily and appropriately. Functionality refers to the extent to which the system operates in the way it is structured, and is expected to perform, as the users' desire it to. Users tend to use functional and usable surgical interfaces more frequently. Usability and functionality are quality characteristics that evaluate the interface design [5].

The questionnaire that is designed to investigate the importance of usability and functionality factors for a surgical interface from the perspectives of surgeons has been prepared. Initially, the description of the questionnaire is given to the surgeons. Then, the questionnaire is given to them. The questionnaire mainly consists of two parts. The first part has been designed to elicit information about the demographic profiles of the respondents. The second part of the questionnaire asks respondents to indicate their opinion about the importance of the items related to usability and functionality.

In this study, the usability factors examined in the questionnaire are navigation, interaction, learnability, ease-of-use, response time, memorability, and efficiency and the functionality factors examined in the questionnaire are user guidance or support, data security, autorun, customizability, achievability and accessibility, ability to interact with external systems, and validation. A total of 12 questionnaires have been collected from the surgeons. Only one respondent is female; the average age of the respondents was 45. Seventy-five percent of the respondents were from Turkey. Forty-two percent of them had work experience of more than 15 years. Sixty-nine percent of them performed more than 15 surgeries over the last three years. Only seven of them use a computer-assisted navigation system in their operations.

All the items related to usability and functionality were measured using a 7-point Likert scale, with 1 representing "Not important at all" and 7 representing "very important." The mean and standard deviation of the items related to usability and functionality are shown in Table I. Response time, efficiency, and ease of use are found to be the most important among the usability factors, whereas interaction, navigation, and memorability are the least important factors. Achievability and accessibility, autorun, and data security are found to be most important among the functionality factors, whereas the ability to interact with external systems, customizability, and validation are found to be the least important factors.

Table 1. Average and standard deviation of usability and functionality factors.

Usability	**Average**	**Standard Deviation**
Response time	6.50	0.67
Efficiency	6.25	0.62
Ease of use	6.25	0.87
Learnability	6.17	1.19
Interaction	5.83	1.27
Navigation	5.58	1.24
Memorability	5.42	0.90
Average sum	**42.00**	
Functionality	**Average**	**Standard Deviation**
Archivebility and Accessibility	5.83	1.34
Autorun	5.58	1.08
Data security	5.58	1.73
User guidance and support	5.50	1.09
Ability to interact with external systems	5.33	1.23
Customizability	5.25	1.42
Validation	5.17	1.47
Average sum	**38.25**	

Fig. 2 shows the sorting of all the factors in terms of importance. According to the results, the response time, ease of use, and efficiency are the most important factors among the usability and functionality factors. This shows that surgeons give higher importance to the usability-related factors.

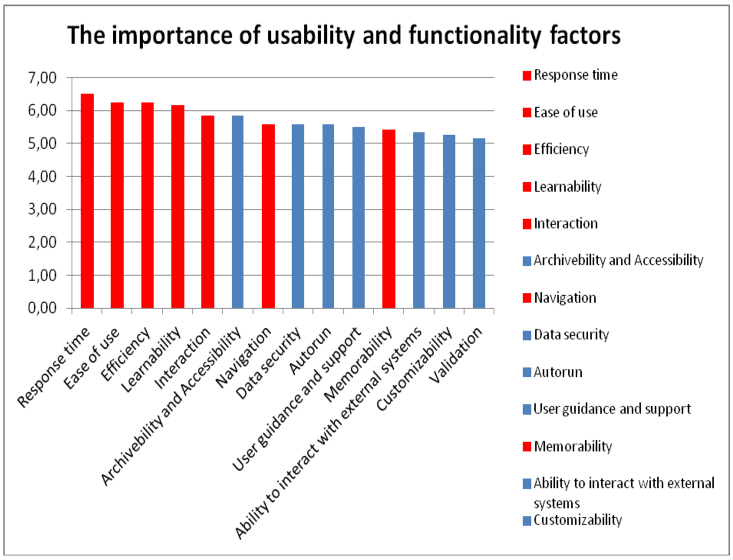

Fig. 2. Importance of usability and functionality factors.

Surgeons want to operate the surgical interface without experiencing any difficulty or trouble. The early review of the initial surgical interface designs has been deemed necessary for the finalization of the correct and detailed designs that will be effectively implemented by the design team. In saying this, it is also evident that the review of the surgical interface designs is focused more on the response time, efficiency, and ease of use than other factors. Therefore, most of the recommendations given to the design team of the surgical interface are aimed at improving the surgical interface's ease of use and efficiency, and are related to the design and placement of icons, menus, toolbars, labels, and screen layout.

4 Development of Surgical Interface

The software architecture of the surgical interface facilitates interactive manipulation, and visualization of 2D and 3D data objects, including medical images. The surgical interface and its development environment integrate the robotic device, data sets, and 3D models (Fig. 3). A 3D graphical user interface of the surgical interface manages the user interaction from various input devices, and renders a menu system. Additionally, data management of the surgical interface provides the means to both import and export the data, including medical images, models, and surgical plans. In its implementation, the data management can accommodate data in various formats, including DICOM. The data management of the surgical interface has the capability to import organ mesh and CAD models, robot CAD model, surgical plans, and to present annotations and warnings. Furthermore, performance monitoring, state logging, and recovery have been considered during the design of the surgical interface.

The surgical interface is developed using Microsoft Visual Studio 2010 Development Environment. The visualization toolkit (VTK), which is an open source and freely available software, is used for 3D medical image processing and visualization.

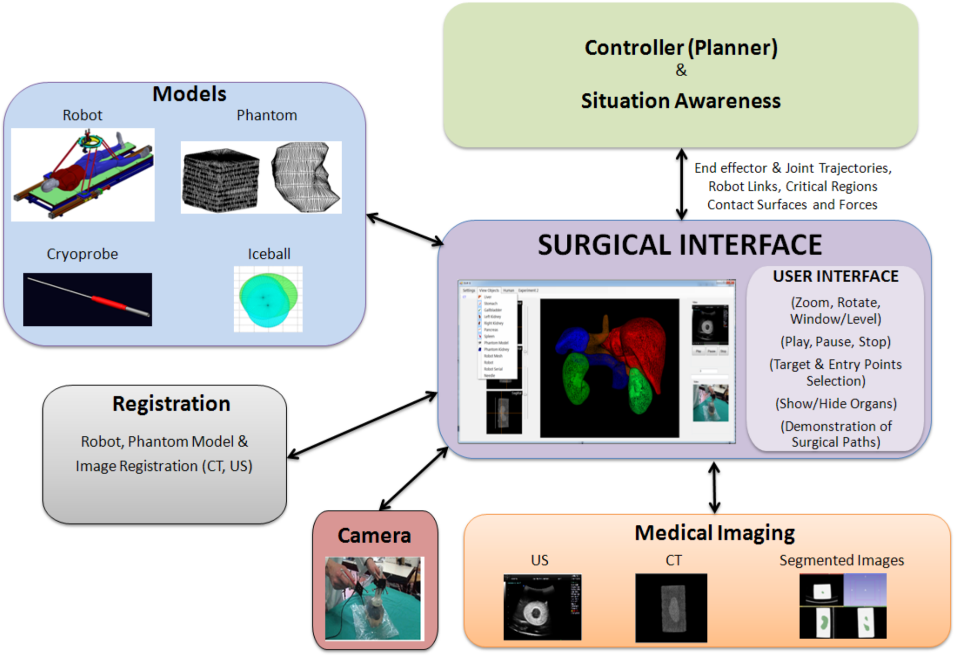

Fig. 3. Surgical interface architecture.

CT images in DICOM format are loaded using the DICOM reader classes of the VTK in the surgical interface. CT images are presented in 3 conventional medical views as axial, coronal, and sagittal. Additionally, the surgeon can adjust the window level of the loaded CT images. Moreover, the corresponding anatomical CT slices can also be rendered on the human model axis, which enables the monitoring of the anatomical view with the surgical device robot. US images that demonstrate an online scan of the kidney model, which gives the design team the capability to show the surgical task through the surgical interface, is integrated into the surgical interface. US images of the kidney phantom and camera data obtained during US image gathering are integrated inside the surgical interface.

Segmented models of the phantom (kidney) from the CT images are constructed to register CT images with the 3D kidney phantom model (Fig. 4). The 3D model of the kidney phantom is produced by extracting the boundaries of the kidney from the CT images. Further, the extracted boundary points are triangulated to create the surface mesh model. This operation is also performed to construct the phantom's outer surface. It is possible for the surgeon to zoom, to pan, and to rotate the organ to better assess the case and establish a more accurate diagnostic (Fig. 5).

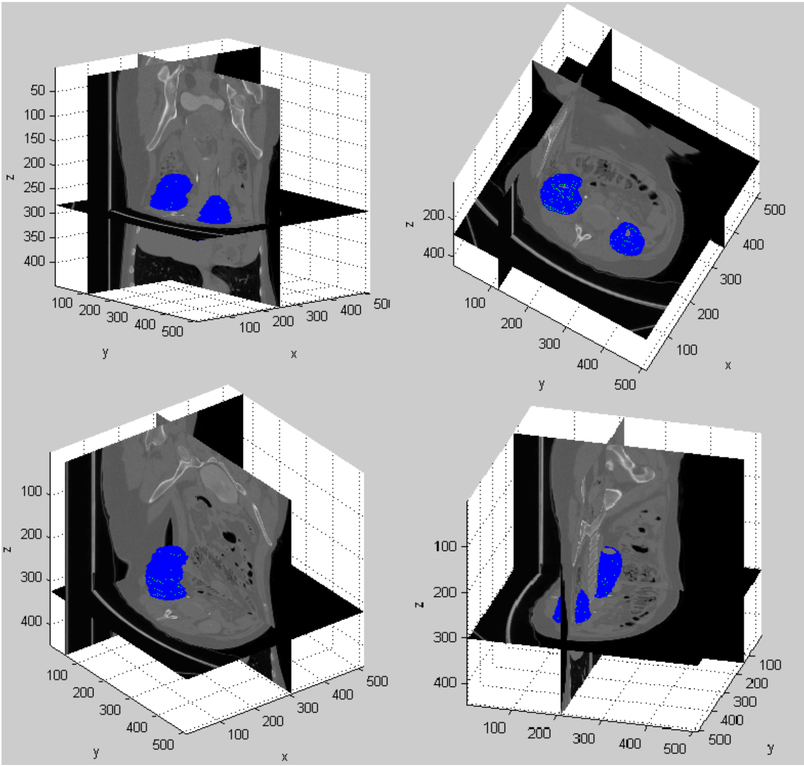

Fig. 4. Kidney model detected from real CT images. Mesh results superimposed on the anatomical images.

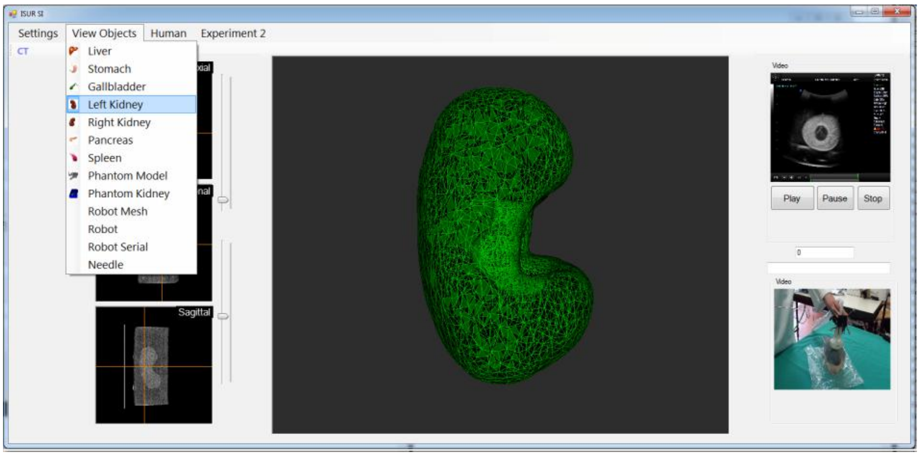

Fig. 5. Selection of the left kidney on surgical interface.

The surgeon can access the phantom anatomic data (namely axial, sagittal, coronal views of the CT images) and the segmented organs during the puncturing task in a surgical intervention in the kidney (Fig. 6). The motions of the cryroprobe and the US probe can be displayed on the surgical interface to the surgeon to demonstrate the puncturing task in a surgical intervention in the kidney (Fig. 7).

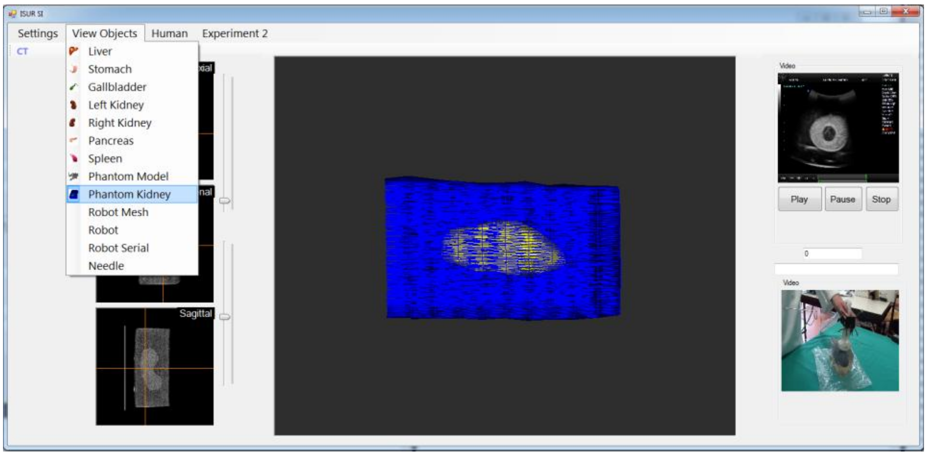

Fig. 6. 3D phantom model of the kidney phantom on surgical interface.

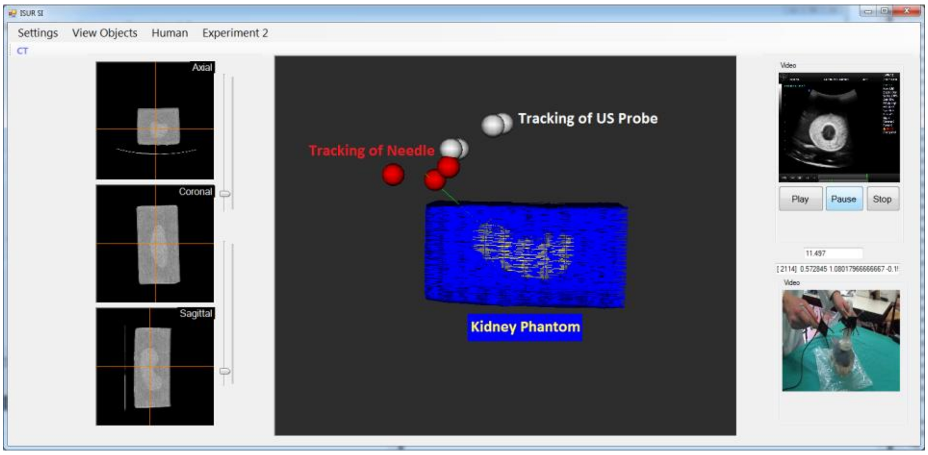

Fig. 7. Demonstration of surgical task while tracking with US probe on surgical interface.

5 Evaluation of Surgical Interface with One Surgeon

One surgeon from the Urology Department of Istanbul Faculty of Medicine, Istanbul University participated in the experiment (Fig. 8). The surgeon was asked to monitor the task where the simulated autonomous puncturing operation is displayed with different surgical interface versions, and to report his impressions about the surgical interface after the experiments. The experiments were conducted in a quiet area of the laboratory.

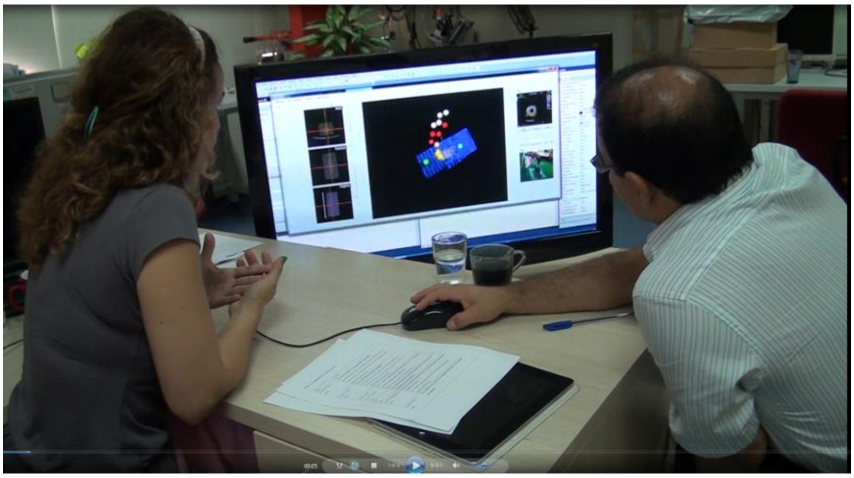

Fig. 8. Surgeon while evaluating the surgical interface.

The surgeon found the CT image displayed on the interface with its axial, coronal, and sagittal views useful. This supports the efficiency of the surgical interface. The surgeon thought it was easy to zoom, pan, and rotate the operation area using the surgical interface. Thus, the proposed surgical interface considers the ease of use factor of usability. The surgeon also thought that the response time of the surgical interface to his requests was fast.

The surgeon would have liked to see a small screen at the top right on 3D view that demonstrates the final position on the tumor with ablation completed. The surgeon felt this screen would help any surgeon to monitor how much he deviates from the target area. The surgeon stated that he prefers to select the entry and target points using the CT images. Additionally, he would like the surgical interface to present various surgical plans with information on the critical regions. Thus, he would be able to select the optimum surgical plan based on his experience.

6 Conclusion

A surgical interface needs to be designed with the surgeon at the center. The quality of a surgical interface design is able to increase the effectiveness of a surgeon's performance if its design considers the surgeon'' desires. Therefore, the proposed surgical interface has been designed considering the surgeon's preferred usability and functionality factors.

The proposed surgical interface facilitates the visualization of 2D and 3D data objects, including medical images, and the integration of surgical tools such as a cryoprobe, and 3D models. A 3D graphical user interface of the surgical interface manages user interaction from various input devices, and renders a menu system. The surgical interface has the capability to import surgical plans.

For further research, we plan to increase the number of surgeons to get more feedback about the proposed surgical interface. Additionally, we will start integration of the surgeon's suggestions into the existing surgical interface to obtain the optimum surgical interface design. Furthermore, various combinations of the surgical interface will be developed to decrease the cognitive workload of the surgeons when they are interactively performing the puncturing task in a surgical intervention in the kidney.

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