Evaluation of Interventional Planning Software Features for MR-guided Transrectal Prostate Biopsies

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***Abstract* — This work presents an interventional planning software to be used in conjunction with a robotic manipulator to perform transrectal MR guided prostate biopsies. The interventional software was designed taking in consideration a generic manipulator used under the two modes of operation: side-firing and end-firing of the biopsy needle. Studies were conducted with urologists using the software to plan virtual biopsies. The results show features of software relevant for operating efficiently under the two modes of operation.**

Keywords—MRI-guided intervention, prostate biopsy, intervention planning software, computer-assisted interventions

I. Introduction

The standard approaches for prostate biopsies include transrectal ultrasound (TRUS)-guided biopsy, MR-imaging guided biopsy (MRgPBx), and MR-ultrasound (MR-US) fusion biopsy [1]. TRUS-guided biopsies employ either extended-sextant (10-14 cores) or saturated (22-45 cores) biopsy-schemes, but they either have a high false-negative rate of detection, under sampling of prostate cancer (as in the case of the former), or high rate of morbidity/over-sampling (seen in the latter) [2]. On other hand, MR-guided biopsy of the prostate is the most sensitive modality to accurately detect and sample prostate lesions, however this requires use of MR-compatible instruments, prolonged positioning of patient in prone position within the MRI gantry, and extended occupation of usage-slots of MR machines [2, 3]. The prolonged patient positioning and extended use of the MR scanner can be reduced by designing a software with suitable features that enables the operator to plan biopsies efficiently and with less duration.

Independently of the modality, biopsies are performed using a transrectal probe in either side-firing or end firing mode (as illustrated in Fig. 1). The chosen trajectory of the needle-exit directly affects (a) patient positioning, (b) surgical technique and probe movements to obtain the biopsy, and (c) cancer detection rates [4, 5]. Theoretically, both probes provide good visualization under optimal conditions and patient positioning; in many institutions, it boils down to surgeon-preference and experience. Thus, it is imperative to understand the relation among the mode of operations, visualization schemes offered by the software, and its effect on the duration of planning the biopsy procedure.

The transrectal probe may also benefit from controlled actuated motions to accurately target prostate tissue. As a consequence, several robotic manipulators, compatible with an MR system have emerged [6–12]. These include a commercially available MR-compatible system that uses a

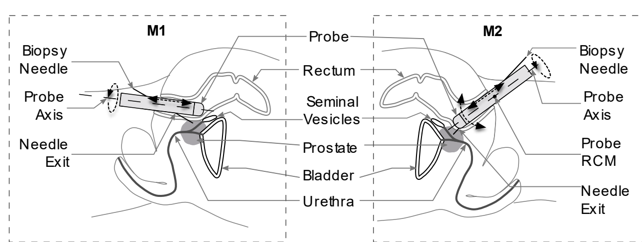

Fig. 1. The two modes of operation offered by a transrectal probe. The probe has an internal compartment for the needle to be guided into position inside the patient's rectum. The probe's manipulation is applied based on these two modes. In M1 (side-firing), the needle exits from the probe's side, along its circumference whereas in M2 (end-firing) the needle is released from the distal tip.

tripod to install the needle guide [7], an MR-compatible apparatus that uses a 3-axis Cartesian stage for the robotic arm [12], and an iterative development of an MR-compatible device [11]. Additionally, these manipulators make use of special actuation mechanisms, such as piezoelectric motors [13–17] or pneumatic actuators [8, 9, 11]. Therefore, biopsy planning also includes the component of analyzing motion of robotic manipulator using the software for intervention planning.

In this work, we present user studies of a software interface for planning MR-guided interventions of the prostate using a robotic manipulator. We initially introduced the software and results of preliminary usability tests in [18]. The usability tests were conducted to evaluate the software from a technical perspective. The motivation for conducting this study was to understand the features of the software from the end-user's (urologist's) perspective that affect biopsy planning.

The structure of the paper is as followed. Section IIA describes the clinical steps involved during an MR-guided prostate biopsy. An intervention planning software adhering to these steps is presented in Section IIB, and the setup for the evaluation of this software by conducting user-studies is described in section IIC. The results of the studies along with its discussion is presented in Section III followed by the conclusion in Section IV.

II. Methods

A. Steps for MR-guided Prostate Biopsy

The prostate biopsy procedure is broadly categorized into four steps: pre-procedure, imaging, planning, and post-procedure. Under the pre-procedure step, the patient lays on the MR scanner bed in prone position, a transrectal probe is manually inserted into the patient's rectum, a manipulator to actuate the probe is placed on the MR bed (between the patient's legs), the probe is attached to the distal end of the manipulator, the actuation mechanism is then connected to the manipulator, and the MR scanner bed is moved inside the scanner. After the first step, the imaging step commences by MR image acquisition and the acquired images are used in the planning step. Fiducial markers pre-placed on the manipulator and transrectal probe and appears as high intensity pixels on the image. Images are processed for co-registration of the manipulator and transrectal probe with their virtual representations, which are rendered in the intervention planning software. Using the interface of the planning software, the operator plans the biopsy. The software assists with the planning by taking into consideration the constraints imposed by the manipulator. Once the operator determines planning parameters, actuation commands are sent to the physical manipulator for proper positioning of the of the transrectal probe. Once positioned, the physician manually inserts the needle to extract the sample tissue. The physician then may re-adjust accordingly to plan and extract consequent biopsies. Once all the biopsies have been extracted, the post-procedure phase (comprising of sub-steps of pre-procedure phase but in reverse order) is executed to conclude the MR-guided prostate biopsy procedure on the patient.

B. Interventional Planning Software and Manipulator Design

A software with relevant features adhering to steps for MR-guided prostate biopsy was developed in C++ using VTK library (Kitware Inc.) and Qt's GUI framework (Qt company). Implementation details are presented in our previous work [18]. In summary, the developed intervention planning software provides user interaction using three panes and *Slice Viewers* as presented in Fig. 2. The interventional planning software was implemented as a modular system, where each module completes the necessary tasks for the visualization of virtual objects, virtual manipulator control via actuating degrees-of-freedom (DoF), processing of user input through user interaction pane, and positioning of virtual objects in the *Slice Viewers* and rendering pane.

Influenced by previous designs [8, 10, 11, 19], a generic design of the manipulator with four DoF, three rotations and one translation, was used for the studies. At the distal end of the manipulator, a transrectal probe is attached. Under M1, actuation of rotational DoF and translational DoF causes rotation and insertion/retraction of the probe along the probe axis. Whereas under M2, actuation of all four DoFs causes placement of probe inside the rectum with anal aperture as remote center of motion (Fig. 1).

C. Setup for Experimental Studies

For the evaluation of the interventional planning software, studies were conducted with eight urologists with three levels of expertise: novice (less than five years of Urology experience but no experience in 3D scene maneuvering), intermediate (less than five years of experience with experience in 3D scene maneuvering), and expert (at least five years of Urology experience). The evaluation was performed to assess the intuitiveness for subjects to actuate the virtual manipulator through the software for planning prostate biopsies. The performance of each subject when planning a biopsy was determined by two metrics: duration (time it takes to perform a biopsy) and target missed count (number of unsuccessful biopsies, i.e., the subject clicked the "Check Target" button and the needle was not passing through the target). The study had

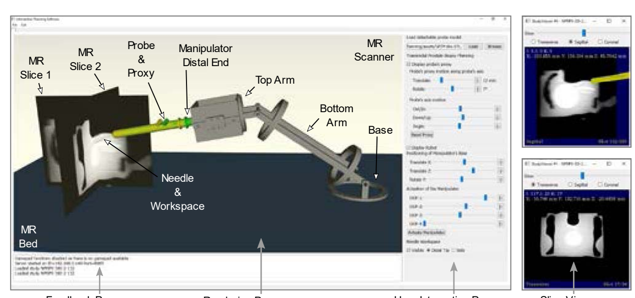

Fig. 2. User interface of the interventional planning software comprised of three major panes: rendering pane, feedback pane, and user interaction pane. In the rendering pane, virtual objects are rendered in 3D scene with respect to MR scanner coordinate system. The 3D scene can be rotated, panned, and zoomed to visualize the virtual objects from different perspectives. Feedback pane provided feedback on system events, such as warnings during planning and confirmation on actuation commands. MR images were visualized in separate 2D imaging windows, called Slice Viewers where, projections of virtual objects (such as probe and biopsy needle) on the MR images were also rendered.

each subject complete three trials in the following order: 3D-M1, 3D-M2, 2D-M1, and 2D-M2. The third trial was conducted for M1 with *Slice Viewers* only. The data collected in these trials was used to compare performance between trials, performance between subjects' expertise levels, and performance between 2D and 3D. Since modes M1 and M2 are different with respect to maneuvering capabilities of the manipulator, the only comparable metric between them is the accuracy of the biopsy.

During the studies, five spheres with varying diameter representing biopsy targets were pre-placed inside the prostate region. As M1 and M2 are used to target different regions of the prostate, trials 3D-M1 and 2D-M1 used the same targets, whereas trial 3D-M2 and 3D-M1 had targets placed in different locations. All trials were timed and conducted independently of each other. For each biopsy target, using the controls in the user interaction pane, the subject had to maneuver the probe's proxy (and hence indirectly maneuver the manipulator), until the target was along the path of biopsy needle. The subject would then click on the "Check Target" button. If the subject was successful in hitting the target, the target would disappear, and the next target would appear. Otherwise, an error message was given in the feedback pane to retry. When the needle hit the target, the time, needle's distance from the center of the target, and the manipulator's configuration was recorded in a log file. Additionally, every interaction of the subject with the system were also logged at regular time intervals.

III. Results And Discussion

Target missed count was recorded for each mode. It represented the number of unsuccessful biopsies, i.e. the subject clicked the "Check Target" button and the needle was not passing through the target. The target missed count for 2D-M1, 3D-M1, and 3D-M2 it was 0, 30, and 9 respectively. Subjects were not able to perform the 2D-M2. Mode 2 requires actuation of all DoFs and as a result, subjects need to visualize the manipulator configuration to assess the pose of probe's proxy, which is not feasible in 2D.

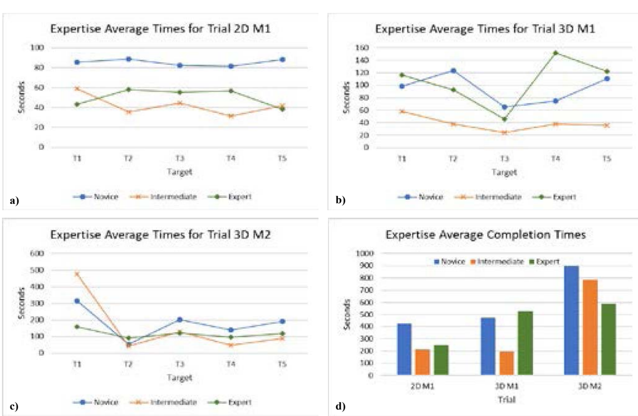

Fig. 4. Comparison of the three categories for the three trials. In (a) to (c), the comparison is made for the trials 2D-M1, 3D-M1, and 3D-M2, respectively, by showing the time it took, on average, for each category to hit each target. In (d), the three trials' time of completion for each category are compared.

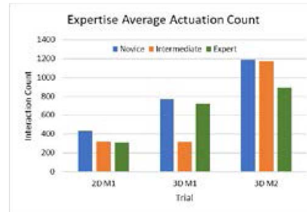

Fig. 3. The number of average actuations required by novice, intermediate, and expert to complete each of the three trials.

Fig. 3 summarizes individual duration required to hit a target by different expertise of subjects under the three modes. The intermediate expertise level were able to complete the trial 3D-M1 significantly faster as compared to novice and expert. This could be due to the fact that these subjects have experience navigating 3D scenes and therefore could much more easily rotate the camera in the rendering pane to view the position of the needle relative to the targeted lesion from different perspectives. In general, the intermediate expertise level did better than experts under 3D-M2 (Fig. 3c) for all targets with exception of the first target. The first target seemed to have given intermediate subjects significant trouble which increased the intermediate average considerably high.

Fig. 4 shows the average number of actuations applied on the proxy by the subjects to complete the trials. Fig. 4 graph resembles the graph in Fig. 3(d) presenting the time needed to complete the trials. Based on the resemblance, it can be deduced that subjects spent about the same amount of time observing the scene as interacting with the proxy.

Fig. 5a - Fig. 5c illustrates the comparison of the 2D-M1 trials vs 3D-M1 trials for each subject within their expertise level, contrasting their performance in 2D vs 3D space. From these results (Fig. 5d), one can conclude that most subjects did comparably better in 2D over 3D, except for intermediates, which was expected due to their prior 3D maneuvering experience. Experts did significantly better in 2D as compared to 3D (Fig. 5c) as it is their conventional method of performing the biopsy procedures, and experts have significant experience in it.

The studies were conducted under certain assumptions. A sub-module is used to co-register the virtual manipulator and probe in the scene with the real counterparts by identifying the fiducial markers on them. This step, although crucial, does not affect the studies as it is a step completed prior to the planning of the biopsy. Additionally, the imaging data used was loaded directly from DICOM files instead of acquiring from the MRI

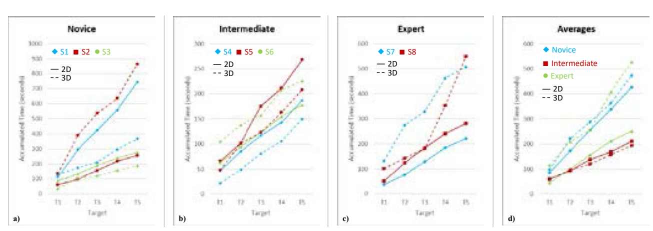

Fig. 5. Comparison of the subjects (S1 to S8) performance in terms of cumulative duration to plan a successful biopsy under 2D-M1 and 3D-M1 modes for the five targets. In (a) to (c), the comparison is made for the three categories: novice, intermediate, and expert, respectively. In (d), all three categories' average are shown together.

scanner on demand. It was sufficient for these studies since the exact position and orientation of the imaging data was taken into consideration. Nevertheless, the source of the data input would change from DICOM files to direct image acquisition. Furthermore, the used imaging data used in these studies was acquired from a phantom representing a pelvic area. The phantom includes the tissue and organs necessary for the biopsy, i.e., prostate, urethra, bladder, and rectum, and were of realistic sizes and properly highlighted in the acquired imaging data. Lastly, it is important to discuss the lack of tissue deformation for these studies. Ultimately, a prostate biopsy needs to consider tissue deformation due to the maneuvering of the probe inside the rectum. Though this was not tested in the study, it would require the intermittent imaging of the prostate and generation of virtual guiding fixtures, like those in [20–22], as the physician maneuvers the probe to consider the deformation and ensure the proxy's needle is penetrating the lesion in the virtual space before proceeding with the real biopsy.

IV. Conclusion

Using an interventional planning software in conjunction with training and familiarization with working in 3D environment can significantly improve the accuracy and duration it takes to perform transrectal prostate biopsies under Mode-2. In case of Mode-1, 2D environment is sufficient for an experienced urologist to perform a biopsy. The results also highlighted the need to perform further studies with a mixture of both visualizations that may reveal important information on improving the subjects' performance while performing a biopsy, i.e., using more than one screen to visualize the scene in 2D and 3D at the same time.

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