Studying the Usability of Forbidden Region Virtual Fixtures for Safer Robotic Assisted Minimally Invasive Surgery

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INTRODUCTION

Forbidden Region Virtual Fixture (FRVF) have been researched in recent years to improve the safety of RAMIS. In fact, most of the commercially available RAMIS systems, such as the da Vinci Surgical System, are currently lacking haptic interfaces, limiting the perception of the surgeon of the patient's anatomy and overburdening the visual channel [1]. The absence of haptic feedback can compromise the procedure's safety as the surgeon is unaware of the force applied with the instrument on sensitive anatomical structures. Moreover, especially for novice surgeons who are not proficient in the control of the surgical robot, the unnotified collision of the surgical tools with the patient's anatomy is an additional risk factor. FRVF can prevent the surgical instruments from getting excessively close to sensitive anatomical structure by returning a feedback force to the surgeon, who is notified of the proximity and can move the instrument in a safer position.
Although FRVF is a promising technique, there are conflicting opinions among surgeons on their real usability, as the force might disturb the execution of the procedure. In this letter, we present a user study on a simplified FRVF scenario, with the aim of evaluating the system's effectiveness and usability.

MATERIALS AND METHODS

A. The FRVF system

The designed FRVF system is based on the knowledge of the real-time relative position in the surgical scene of the anatomical structure to be protected and of the surgical instruments. In absence of exteroceptive sensors, this requires building a computational representation of the interaction. The forbidden region is defined starting from the 3D mesh of the anatomical structure to be protected, which can be obtained from pre-operative images. For simplicity, the structure is assumed to be rigid. The mesh is registered intraoperatively using a set of points of the real anatomical structures obtained using the robot's arm as a localizer. A safety region of width r is identified around the anatomy, as shown in Figure 1.
The position and orientation of the surgical instruments are identified using the robotic arm's kinematic

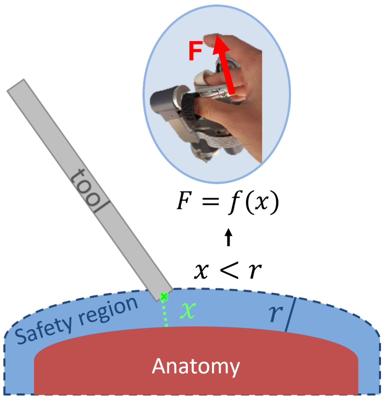

Fig. 1 FRVF system's scheme: when the instrument is inside the safety region, a feedback force is returned to the master manipulator. x is the tool's distance from the anatomy, r is the width of the safety region.

to recover the position of the tool's tip and of the remote center of motion (*rcm*). The entire body of the instrument is represented as a cylinder with radius equal the radius of the instrument and oriented as the segment connecting the tip and the *rcm*. In particular, the shortest Euclidean distance x between the cylinder and the 3D mesh is used.
Whenever the surgical instruments are inside the safety region, a force is computed according to the visco-elastic model in Eq. 1 and returned to the master manipulator.

$$\vec{\boldsymbol{F}} = \begin{cases} k(r-x) \cdot \vec{\boldsymbol{n}} + b(0-\dot{x}) \cdot \vec{\boldsymbol{n}} & \text{if } x \leq r \\ 0 & \text{if } x > r \end{cases} \quad (1)$$

In Eq. 1, k and b are respectively the elastic and the dumping constants, while $\vec{\boldsymbol{n}}$ is the outward normal to the anatomy's surface at its closest point to the instrument. The force is therefore directed to push the tool out of the safety region. A threshold force was set at 5N to prevent damaging to the manipulators' actuators. Notably, no torque is applied to the manipulator, as no desired orientation is imposed.

B. Evaluation of the FRVF system

The evaluation of the system was carried out on a complete da Vinci Research Kit with the contribution

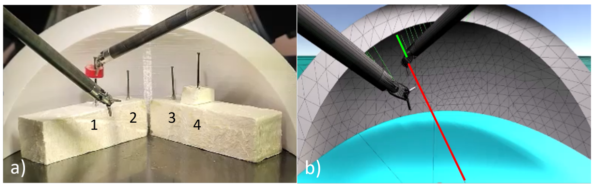

Fig. 2 a) experimental setup. b) computational representation of the interaction. The green line represent the minimum distance of cylinder from the mesh, while the red line indicates the direction of the force feedback to the master manipulator.

of ten un-experienced users. Each user was asked to perform the task in Figure 2: first the red ring is picked up with the right tool, then it is inserted in the first two nails with an up-bottom motion, passed on to the left tool to repeat the movement on the last two nails and finally placed back at the center of the board.The task is inspired by robotic prostatectomy procedures, where the surgeon is forced to work in proximity to the pubic bone structure [2], often colliding with the instrument on it and creating small damages. The goal of the task is to verify whether the presence of the FRVF can reduce the chances of collision of the instruments with the white structure, here representing the pubic bone, without hindering the execution of the task. The experiment was repeated by each user under three different conditions:

- **Control**: execution without force feedback;
- ***r* = 2 cm**: force feedback with safety distance of 2 cm;
- ***r* = 2.5 cm**: force feedback with safety distance of 2.5 cm;

A wider safety region is expected to guarantee a safer execution, but might complicate the execution of the task, as the force feedback starts to act farther away from the pubic bone, where the rings are located.
The order of execution of the tasks was picked randomly for each user to rule out a possible bias in the results. Practice time was given at the beginning of the experiment to reduce the impact of the learning effect.
The utilized values of k and b were respectively 250 N/m and 8 N·s/m. The average and minimum distance from the structure were recorded during the execution of the task as well as the number of collision events. To evaluate the potential hindering of the execution instead, the execution time was used as performance metric.

RESULTS

The distance data are shown in Figure 3. Statistical relevance was established with a Wilcoxon test (significance level 0.05). Both the average and the minimum distance from the anatomy resulted significantly higher when the force feedback was active with respect to the control condition (for r = 2 cm p-values are 0.0257 and 0.0257 respectively, for r = 2.5 cm they are 0.0028 and 0.0312). However, no significant difference is found between the r = 2 cm and r = 2.5 cm conditions.

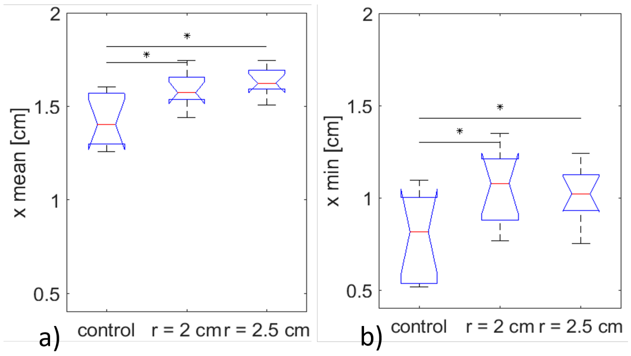

Fig. 3 Average (a) and minimum (b) distance of the surgical instruments from the bone structures.

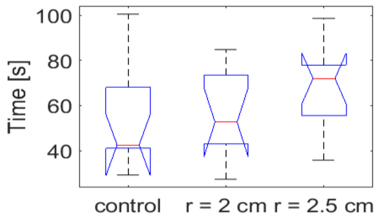

Fig. 4 Execution times.

Additionally, no collision events were recorded while 8 collisions occurred without force feedback. Regarding the execution time, shown in Figure 4, no significant differences were found among the three experimental conditions, even though a trend of increasing times is visible.

DISCUSSION

Results show that the tested FRVF system is effective in preventing collisions and allows to perform the tested task within a safer distance from the simulated pubic structure. Moreover, the force feedback generated for the two tested values of the safety radius r did not significantly hinder the execution of the task, which was carried out with execution times comparable to the control. These results suggest that, when the force parameters are properly tuned for a specific application, the FRVF can bring a significant advantage to the user. The next step will be to extend the user study to a pool of surgeons to have a more robust evaluation of the system's usability. Additionally, we plan to include an AR interface in the system to get a comparison of the usefulness of different types of augmentation for collision avoidance.

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