Design and Evaluation of an Intraoperative Safety Constraints Definition and Enforcement System for Robot-Assisted Minimally Invasive Surgery

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INTRODUCTION

Most of the studies and progresses in surgery have focused on minimizing the invasiveness of surgical procedures. In the last decades, there has been a significant methodological shift in several surgical procedures: surgeons do not directly see and, especially, do not directly touch the anatomical structures on which they operate. In fact, advances in video imaging, endoscopic technology and robotic instrumentation have made a definite transition from open to minimally invasive surgery possible [1]. However, surgical robots are still tele-operatively controlled by the healthcare professional and the human error remains considerably high. In minimally invasive surgery, even when performed with a robotic device, the most common complication is accidental damage to nerves, veins and arteries [2]. This may cause dysfunctions, heavy bleeding and affect the outcomes of the surgical procedure. To address this issue, we developed and tested a system for the intraoperative definition of safety constraints which generates a repulsive force on the robotic tool when it tries to enter the constrained region.

MATERIALS AND METHODS

Safety constraints can be defined as "control strategies" that can be used in robot-assisted manipulation tasks to assist the procedure by anisotropically regulating motion [3]. This is achieved by comparing the robotic tool position with respect to known restricted regions and then modulating the master command to prevent the manipulator from entering those regions.

The implementation of the constraint enforcement method is achieved by placing a virtual damped spring between the robotic tool and the constrained volume. The viscoelastic enforcement function is

$$\mathbf{f}_p = k_p(\mathbf{p}_d - \mathbf{p}_c) + k_d(\dot{\mathbf{p}}_d - \dot{\mathbf{p}}_c)$$

where $\mathbf{f}_p$ is the constraint force vector, k_p and k_d are the proportional and derivative gains, and $\mathbf{p}_d$ and $\mathbf{p}_c$ are the current and desired tool position respectively. If the robotic tool is out of the constrained region, the desired position is coincident with the actual one and the force will be nil; in case it violates the constraint, the desired tool position is set to be the nearest point on the surface of the bound region, then creating the virtual linkage which finally generates the repulsive force (Fig. 1).

To generate the constrained region, the system allows the surgeon to define an intraoperative area above the

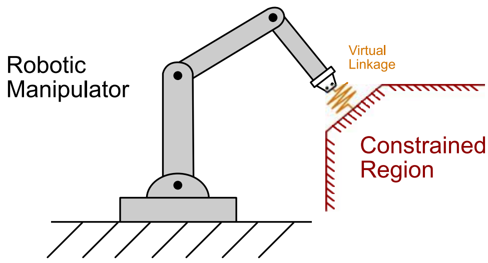

Figure 1. *The safety constraints generate a repulsive force thanks to the virtual linkage.*

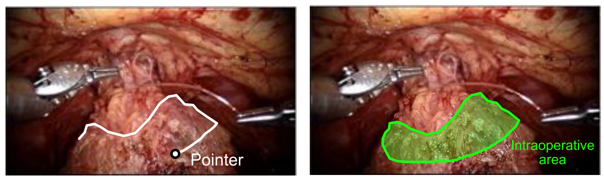

Figure 2. *By moving the pointer, the surgeon can draw the safety area freehand.*

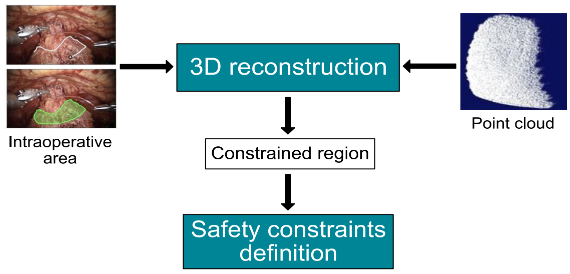

Figure 3. *Operating scheme of the system.*

patient's anatomical structures. This is achieved by moving a pointer, shown on the surgical console viewer, with the same master controllers the surgeon uses to perform the surgical procedure (Fig. 2).

During the surgical procedure, a point cloud of the patient's anatomical structures is produced by exploiting the disparity map between the images of a stereoscopic camera. The previously drawn area is projected to identify the portion of the point cloud belonging to the anatomical structure that the surgeon intends to select. In this way, a repulsive force is generated to prevent the robotic tool from entering the constrained volume, thus avoiding damage to the selected anatomical structures (Fig. 3).

To validate the system, we exploited the da Vinci Research Kit master console (Intuitive Surg. Inc.) and a virtual simulation environment we previously developed [4]. A virtual partial nephrectomy simulation was created with anatomically correct models of a renal tumour and renal arteries, both placed on a stand-in for the kidney

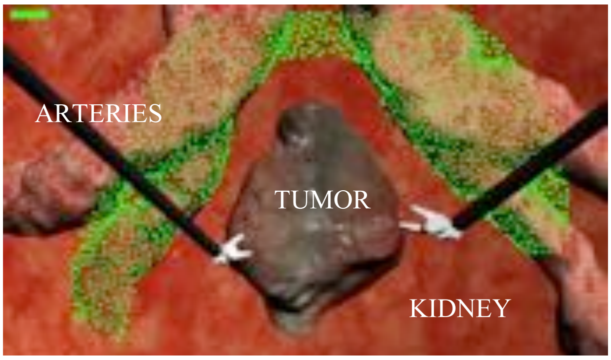

Figure 4. *The virtual partial nephrectomy simulation. The constrained region is represented by the selected points coloured in green. Their colour changes from green to red according to the safety area - tool distance.*

(Fig. 4). Ten volunteer candidates (with no experience with robotic tele-operation) were asked to perform the removal of the tumour by using virtual tools whilst trying to avoid the collision of the robotic tool with the renal arteries. Each participant performed the task 6 times, alternately under two different modalities: in the first unconstrained modality, the tumour removal is carried out without any feedback; in the second constrained modality, the candidate has to define an area enclosing the renal arteries so that the execution of the task is supported by the force feedback generated from the surface of the constrained region, as well as visual aids indicating the distance between the tool and the safety region. The proportional and derivative gains of the viscoelastic enforcement function were set to 1000 N/m and 10 N*s/m, while the maximum constraint force was imposed to be 4 N. In order to quantify the outcomes, the mean number of collisions of the robotic tool with the renal arteries, the mean total duration of the collisions (in seconds), the mean percentage of healthy tissue improperly removed in addition to the tumor (defined as the difference between the removed tissue surface and the tumor surface divided by the tumor surface) and the mean task execution time (in seconds) were analysed for each candidate and each modality. Due to the small sample size, non-parametric statistical significance tests were used to compare the performance of the users in the constrained and unconstrained task. The Wilcoxon rank sum test was then employed in MATLAB. Statistically significant effects were assessed at $p < 0.05$.

RESULTS

The distributions of the number of collisions, the total collisions time and the percentage of removed healthy tissue for the *constrained* and *unconstrained* task are shown in Figure 5 and their median values are reported in Table 1. The results suggest that the safety constraints have enhanced the accuracy in performing the task compared to the *unconstrained* case, reducing all the parameters. Furthermore, safety constraints reduced the variability of the performance among the users compared to the *unconstrained* sets. Finally, the average task time (considering only the duration of the tumour removal) show that users completed the constrained task faster:

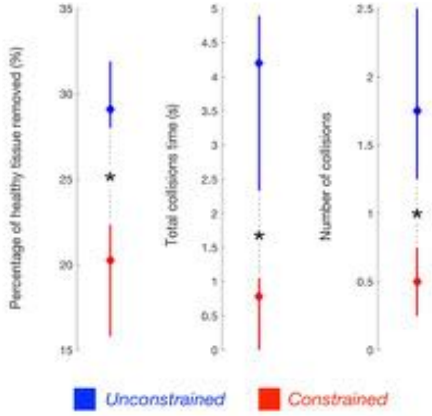

Figure 5. *The accuracy metrics are reported in terms of median (diamond marker) and 25^{th} – 75^{th} percentiles (vertical bar) across the subjects.*

	Unconstrained	Constrained	p
Number of collisions	1.75	0.50	<0.001
Total duration of collisions (s)	4.20	0.78	0.0013
% of healthy tissue removed	29.09	20.25	<0.001
Task execution time (s)	40.81	36.58	<0.001

Table 1. *Task performance metrics median values across the users in the unconstrained and constrained mode.*

32.6 sec. if *constrained.* vs. 40.8 sec. if *unconstrained*, $p<0.001$. This can implicitly imply ease of use of the system and reduction of cognitive load.

CONCLUSION AND DISCUSSION

We presented a system for the intraoperative definition of viscosity-based constraints on a safety area. We tested this system on a virtual reality task and the results showed higher performances in terms of accuracy and time with respect to the traditional unconstrained case. This research focused only on a small group of candidates. For a higher statistical determinism, it will be necessary to carry out experiments involving a larger sample size. Additionally, repeating the study on medical participants would increase the impact on the research field.

ACKNOLEDGEMENTS

The current work is part of the “SMARTsurg” (SMart weArable Robotic Teleoperated surgery) project, which has received funding from the European Union’s Horizon 2020 research and innovation programme.

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