



**POLITECNICO
MILANO 1863**

Implementation and assessment of Assistance-as-Needed Virtual Fixtures for Surgical Training with a *da Vinci* surgical robot: an experimental study

Politecnico di Milano - Master of Science in Biomedical Engineering

Academic year 2022/2023

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1 Introduction

Since the introduction of Robot-Assisted Minimally Invasive Surgery (RAMIS) in the healthcare market, patients have benefited from the diminishing of post-operative complications and an increase in the safety of procedures, while surgeons have been empowered by sophisticated robotic systems allowing the execution of complex tasks in adverse contexts.

Surgical teams have been joined by robotic systems because of the number of benefits that result from the collaborative effort of the surgeon and the robot, combining the know-how and adaptation skills of the former and the high accuracy and stability of the latter. Such a synergistic perspective highlights the role of the Human-Robot Interaction (HRI) paradigm, which involves all aspects of understanding, designing, and evaluating robotic systems for use

by or with humans [1]. Most of the surgical robotics solutions on the market consist of a teleoperation console that interfaces with the practitioner and, separate from it, the surgical robot itself, which mimics the movements of the surgeon in real-time. This setup allows for higher motion accuracy, tremor filtration and magnified viewing of the surgical area; nonetheless tactile forces, friction and texture perception are excluded from the so crucial visuo-haptic feedback loop that would guide the surgeon in a standard "non-robotic" procedure.

This work, specifically, studies and evaluates the role of Virtual Fixtures in the context of surgical training. Virtual Fixtures (VFs) are high-level control strategies employed for assisting humans in man-machine collaboration tasks [2]. In the context of surgical robotics, VFs assist the surgeon by providing haptic guidance at the level of the "master" manipu-

lator, generating mechanical forces and torques which re-direct the motion of the surgeon’s hands. These assistance strategies may be most beneficial in the training process that aspiring surgeons undertake, which often takes place in a simulated virtual environment. Exploiting the customizability of simulated surgical tasks together with the implementation of VFs will enhance the process of learning key surgical skills, in terms of performance, retention and transfer.

2 State of the art

Surgical robotics companies usually commercialize a simulation framework in parallel to clinical robots. A survey of the most relevant training simulators on the market was conducted in [3], a review that also assesses the suitability of virtual environments as comparable to the one of dry-lab setups. However, since no commercially available clinical system implements a force-based assistive modality similar to the one of virtual fixtures, none of the training simulators employ VFs either. The role of such assistive strategies in a real surgical scenario is still uncertain and shall be assessed only through an extensive clinical trial, and as a matter of fact the vast majority of training protocols implementing VFs regards *ad-hoc* systems like [4], which are limited both in terms of tasks implemented and in terms of evaluation protocols. Indeed, few studies [5] have evaluated the trainee’s performance on multiple diverse tasks and over the course of multiple training days, and none has yet investigated the role of haptic assistance on skill retention and skill transfer.

This work proposes an evaluation of the role of VFs in surgical training with a multi-day experimental protocol articulated in two phases, designed in order to highlight the difference in the transfer and retention of skills between a control group and an assisted group.

3 Materials and methods

3.1 Surgical Simulator

This research was conducted on a *daVinci*® surgical robot integrated with the open-source dVRK [6] framework. The Master Tool Manipulators (MTMs) of the *daVinci*® are in fact equipped with motors usually employed for the sake of homing and calibration; the VF forces and torques are generated by energizing these motors according to the inverse kinematics of the manipulators. A ROS [7] framework manages the communication between the teleoperation console of the dVRK and the virtual surgical scene, which is built upon the Unity® physics engine: therefore, the real Patient-Side Manipulators (PSMs) do not move during teleoperation, as the joint coordinates are communicated only to the virtual 3D objects.

The simulator comprises eight surgical tasks, four of which (*Path*, *Rings*, *Pillars* and *Exchange*) are simplistic training tasks built with objects of simple geometry, while the remaining four (*Liver Resection*, *Nephrectomy*, *Thymectomy* and *Suturing*) emulate *in-vivo* surgical procedures and are therefore more realistic. Fig.?? collects snapshots of the tasks. All of these are constructed and set-up in order to be as challenging as possible in relation to a specific surgical skill. A set of fundamental pre-operative and intra-operative skills that any robotic surgeon should acquire during training was proposed in [8]. Specifically:

- *Path* and *Liver Resection* require articulate wrist motion and stability
- *Rings* and *Nephrectomy* survey the depth perception skills
- *Pillars* and *Thymectomy* are hand-eye coordination tasks
- *Exchange* and *Suturing*, both bi-manual tasks, challenge the capabilities in terms of instrument exchange

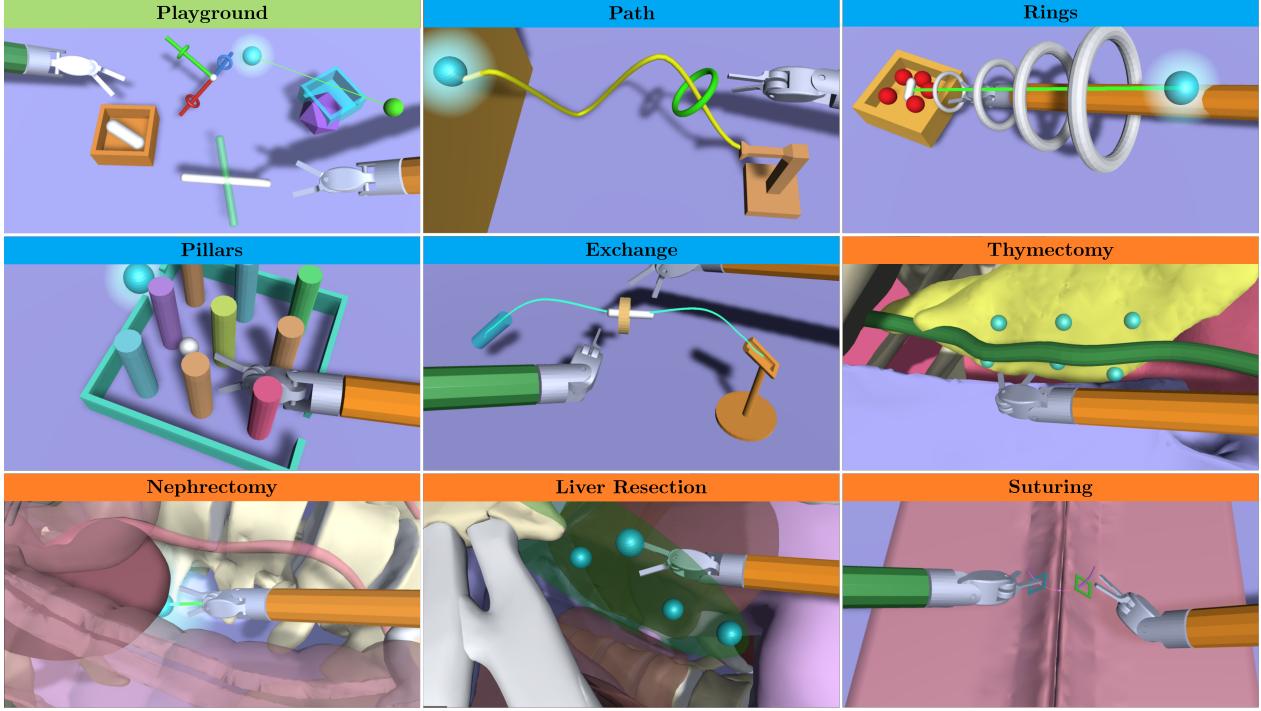


Figure 1: *Snapshot of the simulated surgical tasks, with the respective denomination. Training tasks have blue headlines, while realistic evaluation tasks have orange headlines. Playground is a propaedeutic task and isn't featured in the*

Each training task having a corresponding emulated surgical procedure will allow, during the experimental phase, to evaluate the transferability of skills.

The simulator also exploits 3D viewing capability of the High-Resolution Stereo Viewer (HRSV) installed on the teleoperation surgical console: two virtual cameras are positioned in the Unity[®] scene at a distance of 5.3mm, as their feed is sent separately on the left and right oculars at the console achieving a three-dimensional perception of the virtual environment.

3.2 Virtual Fixtures

During teleoperation the surgeon is de-coupled from the patient: this is necessary in order to exploit the benefits of a robotic solution, which requires the system to be "in between" the practitioner and the patient in order to enhance the surgical experience. However, this de-coupling removes the haptic component from the motion control feedback loop of the

surgeon, who is used to relying on the sense of touch when operating with a conventional approach. For this reason, this work analyses how the introduction of haptics in a virtual surgical environment may enhance the training phase, acting as a guidance and error-correcting medium.

In the context Virtual Fixtures, also known as Active Constraints, a haptic force is applied to the manipulators at the surgical console, which re-directs the motion of the surgeon's hands in case of improper or unsafe maneuvers. The magnitude and direction of the VFs force are computed from the PSM position and orientation relative to the surgical space and the position of objects in the scene, in a true feedback fashion. A transformation mapping the PSM operating space to the MTM console space is necessary in order to sensibly use the feedback force as a corrective strategy.

$$\mathbf{f}_{MTM} = T_{PSM}^{MTM} \cdot \mathbf{f}_{PSM} \quad (1)$$

3.2.1 Distance Mapping

Most of the assistance strategies implemented here will use the distance from the PSM to the target or obstacle as the primary metric for determining the intensity of the feedback force or torque. However, different surgical tasks and situations require a level of control over how the distance is taken into account, and for this reason a sigmoidal mapping function was employed for the normalization of the linear or angular error into a suitable interval. Specifically, such mapping is formulated as:

$$f_{map}(x) = \frac{1}{1 + e^{\frac{\delta \cdot w(x-t-h)}{0.2}}} \quad (2)$$

with $\delta = +1$ for guidance VFs and $\delta = -1$ for avoidance VFs. Here:

- t is the fixture *threshold*, hence the value at which the sigmoid starts to significantly increase from zero
- h is the distance from the threshold at which *half* of the maximum force is provided
- w controls the *width* of the linear region, hence the steepness of the curve

For example, if $t = 2\text{mm}$ and $h = 3\text{mm}$ the surgeon will start to feel a force for errors higher than 2mm , and at 5mm he/she will half of the maximum force delivered.

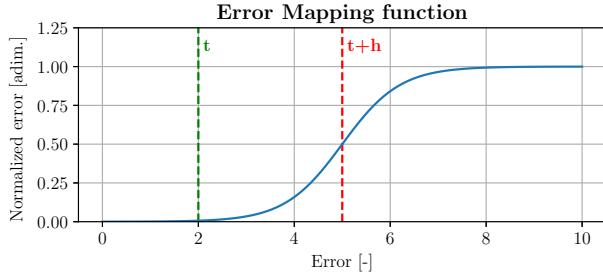


Figure 2: Plot of the Error Mapping function. The position of t and $t+h$ can be set manually to achieve a suitable behavior of the assistance strategy

3.2.2 Trajectory Guidance

A *Trajectory Guidance Virtual Fixture* aids the surgeon in following a reference trajectory and maintain-

ing the correct orientation of the surgical tool. For this VF, the feedback force is computed as the sum of a viscous and an elastic contribution, weighted by the parameters k and η respectively.

$$\mathbf{f} = k \cdot \mathbf{d} + \eta \cdot \begin{cases} \mathbf{d}, & \text{if } \mathbf{v} \cdot \mathbf{d} < 0 \\ \text{rotate}(\mathbf{v}, \theta, \mathbf{r}), & \text{otherwise} \end{cases} \quad (3)$$

$$\mathbf{T} = k \cdot \text{acos}(\mathbf{z} \cdot \mathbf{t}) \cdot \mathbf{z} \times \mathbf{t} + \eta \cdot \text{acos}(\mathbf{z} \cdot \mathbf{t}) \cdot \mathbf{z} \times \mathbf{t} \quad (4)$$

with $\theta = (1 + \mathbf{v} \cdot \mathbf{d}) \cdot \frac{\pi}{2}$ and $\mathbf{r} = \mathbf{v} \times \mathbf{d}$ the angle and axis of rotation respectively

3.2.3 Insertion Guidance

3.2.4 Obstacle Avoidance

3.2.5 Surface Guidance

3.3 Clinical Validation

Two resident surgeons from the *Istituto Europeo di Oncologia*, both regularly performing RAMIS procedures with the *daVinci®* robot, kindly dedicated their time in testing the surgical simulator in all its aspects, from the motion truthfulness to the complexity of the wrist articulation to the invasiveness and viscoelastic balance of the virtual fixtures. Their opinion and expertise were precious and insightful tools that guided the development towards a clinically validated robotic surgical simulator.

3.4 Experimental Protocol

The effectiveness of the haptic virtual fixture paradigm has been assessed with an experimental study where the performance of un-assisted subjects in a control group was compared to the one recorded from subject to whom was provided haptic assistance. Since the aim of this work is to establish the role of VFs in the training context, eight novice subjects with little to no experience with surgical robotics were recruited for the study. Subjects were 25% females and 75% males, between 23 and 27 years of age, all right-handed and either had never teleoperated a sur-

gical robot or did it less than 5 times. Assignment to the control or assisted group was random.

The subjects underwent a week-long training phase:

- On *Day 1*, they were given a concise explanation about the *daVinci®* surgical system, the simulator, haptics, and the training protocol. Later, each subject experienced 5 minutes in a *Playground* environment, purposely designed to understand the elementary mechanics of teleoperation, clutching and object grasping. No performance metric was recorded at this time
- From *Day 2* to *Day 5* they were asked to execute the four training tasks of the simulator (*Path, Rings, Pillars* and *Exchange*), each one for a total of 3 repetitions. Tasks appeared sequentially in a random order, contributing to un-bias the results. At the beginning of each daily session, subjects could interact with the *Playground* task for 1 minute at maximum.
- On *Day 6* and *Day 7* subjects were given a break period and no training was performed
- On *Day 8* they were asked to execute the four validation tasks of the simulator (*Thymectomy, Nephrectomy, Liver Resection* and *Suturing*), each one for a total of 3 repetitions. Again, tasks appeared sequentially in a random order, contributing to un-bias the results.

3.5 Metrics

4 Results

5 Discussion

6 Conclusions

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