Implementation and Assessment of an Augmented Surgical Training Curriculum with a *daVinci* robot: an experimental study

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1 Introduction

The increase of minimally invasive surgical robotics procedures in the last decade demands an increasingly higher number of trained surgeons, capable of teleoperating such advanced and complex systems and at the same time able to take advantage of the benefits of Robot-Assisted Minimally Invasive Surgery safely and effectively.

This work studies and evaluates the role of haptic assistance strategies, also known as Virtual Fixtures (VFs), in the context of enhancing surgical robotics training. These high-level algorithms assist the surgeon by providing haptic guidance at the level of the *master* manipulator, generating mechanical forces and torques which re-direct the motion of the surgeon's hands. VFs 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 an augmented training protocol will enhance the process of learning key surgical skills, in terms of performance, retention and transfer. To confirm this hypothesis, this study conducts a multi-day experimental curriculum that assesses the performance trends and the transfer of skills toward unassisted scenarios, like the clinical one.

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 [1]: this review also assesses the suitability of virtual environments in comparison to that of dry-lab setups. However, since no commercially available clinical system implements a force-based assistive modality similar to that 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 [2], which are limited both in terms of tasks implemented and in terms of evaluation protocols. Indeed, few studies [3] 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 the context of 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 [4] 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 dynamics model of the manipulators. A ROS 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. Figure 1 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 [5]. 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

Since each training task has a corresponding emulated surgical procedure, the experimental phase will allow to evaluate the transferability of skills.
The simulator also exploits the 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, with their feed being sent separately on the left and right oculars at the console achieving a three-dimensional perception of the virtual environment.

3.2 Haptic Assistance Algorithms

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

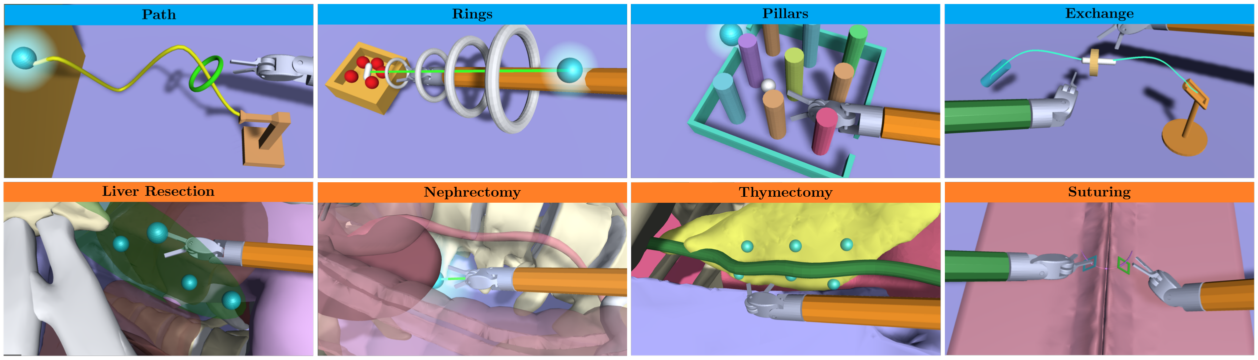

Figure 1: Snapshot of the simulated surgical tasks, with the respective denomination. Training tasks have blue headlines, while realistic evaluation tasks have orange headlines. Tasks on the same column share the same surgical skills required for their completion.

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 haptic assistance in a virtual surgical environment may enhance the training phase, acting as a guidance and error-correcting medium. In the context of 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 that maps the PSM operatory space to the MTM console space is necessary in order to sensibly use the feedback force and torque as corrective media.

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 is employed for the normalization of the linear or angular error into a suitable interval. Specifically, such mapping is formulated as:

$$f_{map}(x) = \frac{1}{1 + e^{5\delta w(x-t-h)}} \qquad (1)$$

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 = 2mm and h = 3mm the surgeon will start to feel a force for errors higher than 2mm, and at 5mm he/she will experience half of the maximum force that can be delivered.

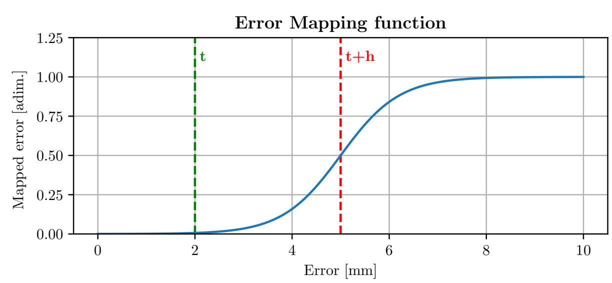

Figure 2: *Plot of the Error Mapping function. The position of t and $t+h$ can be set manually to achieve a suitable behavior of the assistance strategy*

For the purpose of stability and, therefore, safety in the assistive feedback loop, all the VFs implemented have an elastic component, proportional to the error mapped with the sigmoidal function, and a viscous component proportional to its rate of change, which

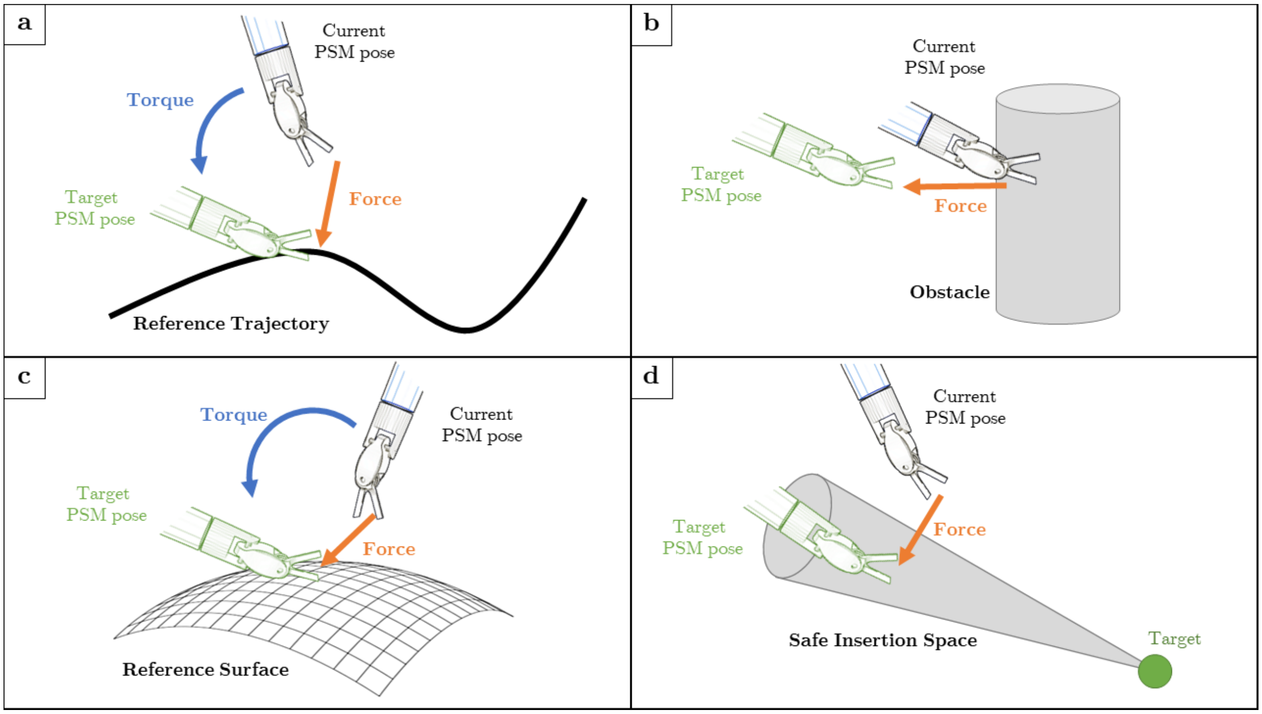

Figure 3: Descriptive graphic representation of the four haptic assistance Virtual Fixtures implemented in the simulator; in all cases, a representative *current* and *target* pose of the surgical tooltip are shown. **a.** Trajectory Guidance; **b.** Obstacle Avoidance; **c.** Surface Guidance; **d.** Insertion Guidance.

damps the possible oscillatory instabilities. The optimal visco-elastic balance is heavily task-dependent and surgeon-dependent, and for this reason it is tuned by manually setting the values of K_f, K_T, η_f and η_T in the equations

$$\boldsymbol{f} = K_f \cdot \boldsymbol{f}_{elastic} + \eta_f \cdot \boldsymbol{f}_{viscous} \tag{2}$$

$$\boldsymbol{t} = K_t \cdot \boldsymbol{t}_{elastic} + \eta_t \cdot \boldsymbol{t}_{viscous} \tag{3}$$

which will ultimately result in the haptic outputs provided to the actuators.
The four types of VFs featured in the surgical simulator are described in the following paragraphs.

Trajectory Guidance Given a reference trajectory - planned in the pre-operative phase - this VF steers the surgeon's hands in order to align the robotic End-Effector (EE) with the closest point on the trajectory itself. The feedback force attracts the EE towards the reference, while the torque rotates it so that it's aligned with the tangent vector at the closest point. Graphics in Figure 3a.

Obstacle Avoidance Having identified a 3D mesh as an obstacle, the distance to the robotic tooltip and its rate of change are used for computing the force feedback. By setting $\delta = -1$ in Equation 1, the sigmoidal mapping function is flipped and higher forces will be generated from small distance errors. Graphics in Figure 3b.

Surface Guidance Similarly to the *Trajectory Guidance* VF, the distance vector to the closest point belonging to a reference surface (planar or non-planar) determines the force feedback, while the torque aligns the EE to the tangent plane at the closest point. Graphics in Figure 3c.

Insertion Guidance This VF aids the surgical insertion of the EE towards a target point, maintaining the path of the tooltip stable inside an insertion cone. Here the feedback force has the same direction as the radial conical coordinate and a magnitude that is proportional both to the distance to the cone centerline and the distance to the target point. With this con-

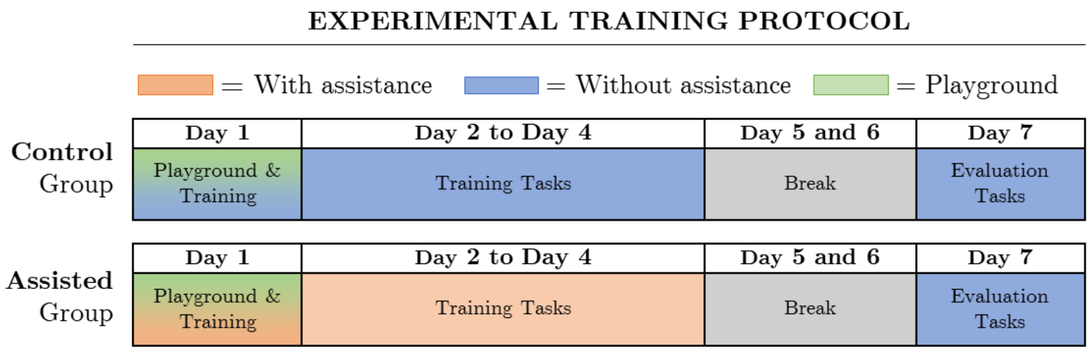

Figure 4: Schematic of the training protocol applied to the subject undergoing the experimental phase. On the days highlighted in orange, assistance was provided to the group indicated; on the days highlighted in blue, the subjects were not assisted by Virtual Fxtures. In green, the *Playground* environment is a propedeutic task shown on the first day only, to familiarize the subjects with the simulator and the *daVinci*® system.

figuration, the PSM's tooltip will be kept inside the reference insertion cone. Graphics in Figure 3d.

3.3 Clinical Validation

Two resident surgeons from the *Istituto Europeo di Oncologia*, both regularly performing Robot-Assisted Minimally Invasive Surgery 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 visco-elastic 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. Moreover, the most expert resident surgeon allowed to have his performance recorded when practicing with the simulator, which will be considered "peak performance" in the experimental analysis.

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 subjects 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 robots 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 surgical robot or did it less than 5 times. Assignation to the control or assisted group was random.

The subjects underwent a week-long training phase, the curriculum of which is schematized in Figure 4. Most relevantly, on the last day, both the assisted and the control group were asked to execute never-seen-before surgical tasks without assistance: this feature allows to evaluate how the skillset acquired during the training phase is transferred to an unassisted and untrained execution.

3.5 Metrics

A quantitative estimation of surgical performance is obtained by combining metrics recorded in real-time during the execution of the task. The simulator logs these metrics autonomously detecting when the user initiates the execution and when the task is completed, at a framerate of 30 Hz. The metrics are:

D	Distance Error (to target or obstacle)
A	Angular Error (to normal or tangent vector)
F	Force Feedback Magnitude
T	Torque Feedback Magnitude
M	Number of drops when exchanging an instrument
C	Fraction of task time spent repositioning

These values are logged at each frame of the task execution and are then averaged once the task is com-

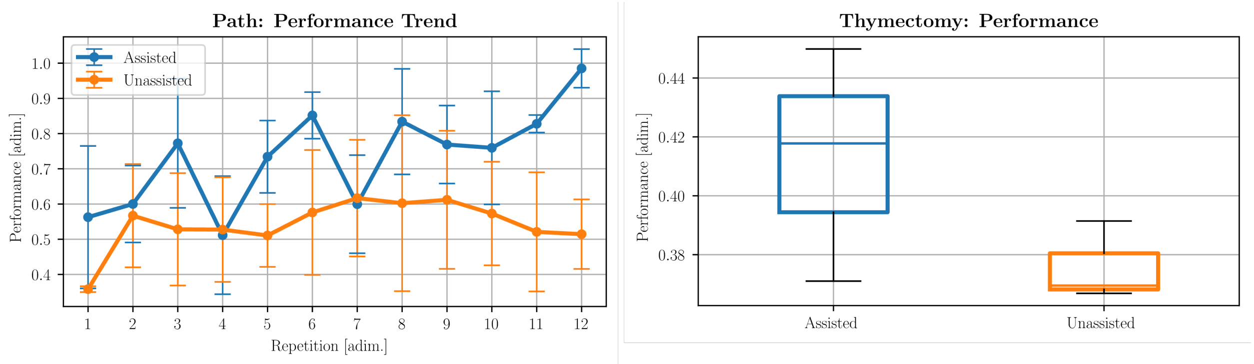

Figure 5: Left: Performance trend of assisted subjects (blue) and unassisted subjects (orange) of the *Path* training task; **Right:** Boxplots of the average performance of assisted subjects (blue) and unassisted subjects (orange) of the *Thymectomy* evaluation task

plete. Metrics are combined with a weighted average to obtain a quantitative performance score: the weights are dependent on the task and the key surgical skills that such a task requires.

Considering "optimal execution" the one achieved by the resident surgeon, the quantitative performance index P is the ratio of the task combined metrics gathered from the optimal execution from the surgeons and the one recorded from the training subjects.

4 Results

Figure 5 shows the performance trends for one of the four training tasks, where the performance at each repetition is the average among the subjects in the assisted or control group. The trends are increasing both for the assisted group and the unassisted group. Most significantly, the performance in the assisted group is consistently higher than the one in the control group. The performance trends shown for *Path* are representative of the other three training tasks (*Rings, Pillars* and *Exchange*).

The performance on one of the four validation tasks recorded on the last day of the experimental phase is also shown in Figure 5 with boxplots. The graph reports the distribution of performances collected from the 4 subjects executing 3 repetitions. Crucially, neither the subjects in the assisted group nor the ones in the control group were guided with VFs on these tasks, nevertheless the performance recorded from the assisted subjects is distributed on higher values for all the tasks. The performance distribution shown for *Nephrectomy, Liver Resection* and *Suturing* mimic the one reported in the figure and referred to *Thymectomy*.

Quantitative results are obtained by comparing, for each task, the mean, standard deviation and median values of performance between the assisted and the control group. Given the data scarcity and their non-Gaussian distribution, the most meaningful conclusions will be drawn from the median values. Apart from *Nephrectomy* showing a slightly reduced median performance on assisted subject (-2.71%), all other tasks present an increase in both the mean and median performance, as high as $+21.54\%$ for *Liver Resection* (*Thymectomy* $+13.07\%$, *Suturing* $+8.44\%$).

The standard deviation in the performance isn't consistent when comparing the two groups.

5 Discussion

Graphs in Figure 5 suggest that VFs grant a performance improvement when executing surgical tasks, an aspect that may be most beneficial in terms of safety and invasiveness when translated in the real surgical context. Under this light, haptic assistance effectively acts as an error-correction strategy which, when applied in real-time, re-directs the EE towards safer spatial regions by acting on the master manipulators gripped by the surgeon.

Concerning the training experience and the associated learning curve, the available results do not show any significant difference when comparing the assisted and the control group, and the hypothesized benefits of VFs regarding this aspect remain to be verified.
The most interesting considerations may be drawn from the difference in performance on the never-seen-before unassisted evaluation tasks, in favor of the assisted subjects. Since for these tasks, which were purposely designed to resemble real surgical scenarios, no haptic assistance was provided to either of the groups, it can be concluded that the introduction of haptic assistance in the training phase actively contributed to the skill transfer from training tasks to surgical tasks. This is arguably due to the integration of the haptic guidance into the visuo-haptic motor feedback loop that acts during teleoperation: VFs therefore contribute to motor learning and, ultimately, improve the establishment of surgical skills in the longer run. As a consequence, the benefits of employing haptic assistance could arise after the training phase as well, when Virtual Fixtures are not in use.

6 Conclusions

This work features the development of a haptic-enhanced VR surgical simulator integrated with a *daVinci*® robot and an experimental study on the role of Virtual Fixtures employed as assistance strategies in the surgical training context. The results of the experimental study have concluded that employing VFs during the training phase of surgical practice leads to improved performance and augmented skill transfer toward real surgical scenarios where haptic assistance is absent.

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