Improving the Development of Surgical Skills with Virtual Fixtures in Simulation

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Abstract. This paper focuses on the use of virtual fixtures to improve the learning of basic skills for laparoscopic surgery. Five virtual fixtures are defined, integrated into a virtual surgical simulator and used to define an experimental setup based on a trajectory following task.

46 subjects among surgeons and residents underwent a training session based on the proposed setup. Their performance has been logged and used to identify the effect of virtual fixtures on the learning curve from the point of view of accuracy and completion time.

Virtual fixtures prove to be effective in improving the learning and affect differently accuracy and completion time. This suggests the possibility to tailor virtual fixtures on the specific task requirements.

1 Introduction

Surgeons training is mainly based on a Halstedian apprenticeship model [4] whereby residents learn by directly assisting an experienced surgeon during the intervention and slowly increase their hands-on experience over time. Considerable ethical, economic and legal problems affecting this approach led to the development of alternative tools to improve of laparoscopic and robotic surgical skills whose goal is to ensure surgeons proficiency before they start operating.

Basic abilities are prerequisites for the correct and safe performance of any surgical gesture and in particular for the execution of robotic surgery procedures. They allow the subject to cope with the perceptual abnormalities that characterize robotic surgery. Surgeons should undergo visuo-spatial and perceptual-motor abilities training to increase their proficiency in presence of indirect mapping between hands and robot and in absence of force feedback. A proper training of visuo-spatial skills allows the subject to redeem the lack of haptic information.

Virtual simulators demonstrated to effectively support the acquisition of the skills required by minimally invasive surgery outside the operating room in a safer, less stressing and cheapest way. Real time data recording constitutes a relevant advantage provided by those tools and makes their application in training and evaluation extremely valuable and effective.

The goal of this work is the assessment of assistive technologies in improving the development of basic skills in surgical training, following the Skill-Rule-Knowledge (SRK) taxonomy [7]. Five different assistance modalities have been

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selected through the analysis of the state of the art and the observation of surgeons experience in the operating room and integrated into a surgical simulator. These assistive technologies have been parameterized by a single function to adapt their behavior to the task proposed in the experiment. A specific experimental design evaluated the improvement in the learning due to these aids.

Section 2 provides an overview of work related to the use assistive technologies in surgical tasks. Each individual aids extracted through the analysis of the state of the art is detailed in Section 3. Section 4 presents the integration of the virtual fixtures in the simulator and the experiment designed to identify assistance outcome. Experimental results are described and discussed in Section 5. Conclusions and future developments are proposed in Section 6.

2 Related Work

The design of different assistive technologies follows the SRK taxonomy proposed by Rasmussen in [7]. The theory distinguishes between skill- rule- and knowledge-based laparoscopic skills. Each behavioral level corresponds to a different degree of familiarity with the task to execute. By keeping into account this taxonomy it is possible to develop learning aids that are effective through the whole training process and to objectively evaluate them.

The skill based level (SBL) groups perceptual-motor and visuo-spatial skills. The skill-based behavior origins from sensory-motor informations, it is strongly automatized and temporally synchronic with the perception of environmental signals [10]. Number of errors and task completion time are the metrics most frequently considered in the evaluation of skill-based abilities. Previous work, based on the introduction of assistive aids in surgical training proves that the introduction of virtual fixtures (VF) in surgical training shorten the time required to develop SBL abilities [9]. These VF can be defined as a set of rules that modify the behavior of the telemanipulated devices in order to improve different aspects such as dexterity, accuracy or repeatability.

One of the most widely applied VF in surgical training is motion scaling (MS). The benefits of MS in robotic surgery is evaluated in [8], where different fixed scaling factors are applied to a tele-surgery system. The improvement in user performance is measured in terms of errors and completion time. The usefulness of virtual fixtures in user assistance is widely accepted and DaVinci surgical system integrates MS and allows the surgeon to set the scaling factor.

In [2] a study of the MS and tremor reduction benefits using the Zeus Surgical System is done. Subjects touch six different targets with an endoscopic tool with and without robotic assistance. When aid is enabled three different levels of motion scaling are used in addition to tremor filtering. Authors state that MS greatly improves accuracy whereas tremor filtering has limited effect.

In [5] pick-and-place tasks in micro-metric workspace are performed using three different modes: unassisted, hand held (with compliant robot) and autonomous. During the experiments fixed motion scaling is combined with a magnified vision on a Steady Hand robot and a LARS robot.

The integration of motion scaling and magnification is also studied in [1]. The paper states that MS reduces the errors when high magnification is used but, on the other hand, this increases the task completion time. Thus the authors suggest the need of trade off between motion scaling and magnification to optimize time and accuracy. Similarly, the work described in [6] deforms robot workspace to provide higher resolution on predefined region of interest: the scaling factor is a function of the distance between the Tool Center Point (TCP) and the target point. Authors also propose a vector-based approach, in which the scaling depends on the direction of motion.

During the initial phases of the training, the cognitive load experienced by the user may be considerably high as he/she has to acquire a relevant amount of information from the environment. By providing information through multiple sensorial modalities it is possible to reduce the cognitive load of the subject and thus ease the learning [11]. Assistive technologies have been applied in many different tasks and modalities, but at the best of author's knowledge, there is a lack in the comparison of virtual fixtures effects and in the evaluation of perceptual modalities for the improvement of the training in robotic surgery.

3 Virtual Fixtures

The analysis of the state of the art lead to the identification of five different assistance tools. Virtual fixtures differentiates for the modality used to convey information to the user and for the modification induced in the master/slave mapping. To isolate the effects of each fixture, all of them the have been defined and applied separately. A modulation function is introduced to control the behavior of the VFs, easing the comparison of the fixtures and allowing the complete control of all the VF through a reduced set of parameters whose effects are easy to understand and set up. All the VFs described in the following exploit the function to provide guidance to the user avoiding tight restriction on movements and leaving him/her the ultimate control over the TCP position.

The modulation function selected for all the fixtures is the five-parameter logistic function, f5PL [3] defined in (1), based on the basic sigmoid function

$$\mathrm{f5PL}(x) = d + \frac{a - d}{(1 + (x/c)^b)^g} \tag{1}$$

where a and d are the expected value of f5PL at zero and at infinite respectively, b controls the slope of the curve between a and d, c is the mid-range concentration and g is the asymmetry factor.

Let $dist_{norm}$ indicates the distance between the target point and the device position normalized by the maximum allowed error. Three regions can be identified in the function domain. Close to the POI ($dist_{norm} \to 0$), the modulation has a constant value of a. This defines a region for dexterous work without disturbances due to VF. When the distance is near to its maximum ($dist_{norm} \to 1$) the modulation tends to b. The initial part of the task is performed in this region, where no changes on the modulation function are required. The two regions are

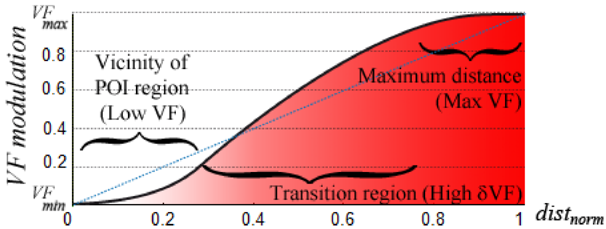

Fig. 1. f5PL modulation function applied to MS for point targeting task

linked by a transition zone that ensures smooth variations. In this zone the modulation varies quickly and the changes in VF's effects are easily noticed by the surgeon. Fig. 1 shows the modulation function and highlights the three regions.

Visual Guidance (VG) provides the surgeon with a guidance tool that acts through the visual sensory channel and originates a motor behavior. VG consists on a graphical representation of the minimum distance vector between the TCP and the goal point that provides surgeons with. information about the proximity of delicate regions and possible collisions while approaching the POI. Fig. (2) shows the VG used in trajectory following.

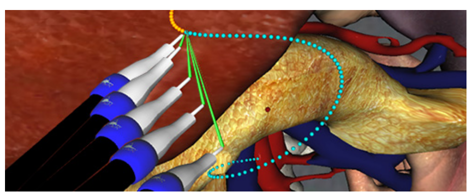

Fig. 2. Sequence of different tool positions and corresponding minimum distance vectors generated by the VG

Audio Guidance (AG) is the transposition of the VG to the auditive domain: errors are signaled to the user through sounds that may correct the motor behavior, helping the surgeon to keep the TCP close to the trajectory. Changes in the properties of the sound signal are controlled by the modulated distance between the tool and the goal point: when the error increases, the elapsed time between two consecutive sound signals decreases and the sample frequency increases. In presence of significative errors, the sound changes are easily perceived and provide a guidance effect.

Motion Scaling (MS) increases the accuracy of the surgeon by modifying the scaling factor between the master and the slave. In bilateral teleoperated systems, the motion of the slave depends on master device input, i.e. $X_S = f(X_M)$. Usually, f includes a fixed scale parameter, whereas MS provides a variable

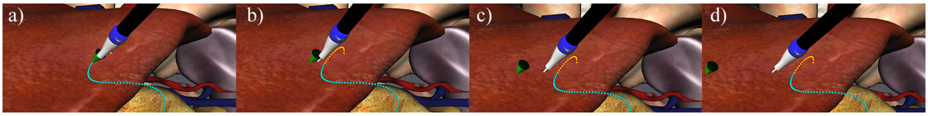

Fig. 3. Sequence of snapshots of the tool with the MS applied in trajectory following

vector-based scale parameter that is function of the error between the TCP and the POI. MS factor is computed and applied independently to each TCP component. Fig. 3 shows a set of snapshots of the application of the MS parameterized to follow a trajectory. The cone represents the position of the tool as if no motion scale was applied.

Magnification (Mag) provides the surgeon with an automated magnification and positioning of the endoscopic camera. This ensures that when the TCP is away from the target point the user has a wide view of the environment, whereas when the TCP is close to the target point a magnified view allows the user to perceive the fine details of the area of interest. Fig. 4 presents some screenshots of Mag: if the TCP is far from the POI, a general view of the scene is provided (Fig. 4.a). As the TCP gets closer to the POI the view is magnified (Fig. 4.b and Fig. 4.c) until the maximum magnification is applied (Fig. 4.d).

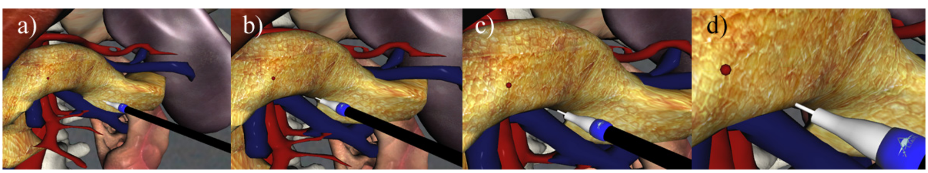

Fig. 4. Snapshots of the VA with the Mag enabled

Force Feedback (FF) guides the tool towards the POI with an attraction force. The direction of the applied force vector corresponds to the minimum distance vector from the TCP to the POI. The behavior of the attraction force follows the spring-damper model (2)

$$F = -Kd_{norm} - C\partial d_{norm}/\partial t. \tag{2}$$

The elastic and damping coefficients (K and C respectively) are the result of modulating two pre-defined coefficients, k and c, using d_{norm} as input parameter, $K = kf5PL(d_{norm})$ and $C = cf5PL(d_{norm})$. This modulation provides a non linearly-varying force that is negligible when the error is small and smoothly reaches the maximum when the error increases.

4 Experimental Design

To evaluate the effects of VFs in robotic surgery training they have been integrated into a virtual environment. The advantages of virtual over real environments are manifold: they allow the full control over the trials parameters and ensure repeatability and provide a portable and low cost setup.

The chosen virtual environment is based on the work described in [12] to which the reader is referred. It provides a reconstruction of abdominal anatomy in which the user can perform surgical tasks such as probing, grabbing, clamping or cutting. The whole simulation runs on a laptop equipped with a 17" monitor, user input and haptic rendering is handled by a Sensable PHANToM Omni. The experimental set up is depicted in Fig. 5.

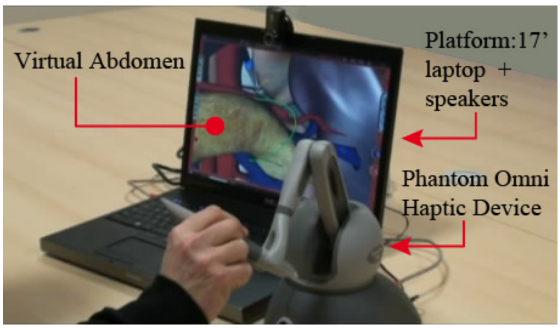

Fig. 5. The experimental setup

The integration of VFs into a virtual environment allows the development of the experiments required to analyze the effects of each VF individually. The designed task requires the user to follow different trajectories defined by 110 points by touching all the points in sequence with the TCP. The organs in the scene restrict tool movements, forcing the surgeon to avoid collisions and to deal with occlusions. The action of following a trajectory in a complex environment with regions to be avoided is a basic and recurrent gesture in many different procedures and it is not strictly related to a particular surgical field. Thus, the performance in trajectory following task can be a good measure of subjects manual dexterity. During the experiment the rendering of forces due to contacts with organs has been disabled to avoid interferences/overlap with VFs. This ensures the same base conditions for all the trials.

The evaluation of any fixture requires the assessment of subject's proficiency without VFs assistance. Thus the first part of the experiment identifies the subject base line performance with 3 VF-free trials. The second part proposes 5 blocks composed by 6 trials, all of them assisted by the same VF, followed by one VF free trial. During the five blocks, scheduled to cover all the considered VFs, the subject faces 6 different trajectories obtained by mirroring and rotating a single original path. This ensures that their difficulty is the same in terms of curvature and length and reduces any learning effect. The six trajectories are presented in a randomized order to avoid any facilitatory effect due to specific orientation sequence. On the contrary, all the VF-free trials are carried out on the same trajectory to exclude trajectory specific bias.

Before the experiment subjects are provided with a short introduction to the experiment goals, the virtual simulator capabilities and to VF. After the introduction, a questionnaire collects subject personal and experience data then the trials are proposed to the subject. Finally, a second questionnaire gets the subjective evaluation of each VF and possible suggestions.

Statistical analyses rely on the improvements in task accuracy and completion time due to virtual fixtures. The analyses isolate and verify the effects of each virtual fixture on the learning process and at identify the presence of significative differences between them. The learning curve is estimated by comparing only the set of VF-free trials, Repeated Measures Analysis of Variance (RM-ANOVA) and Tukey's Honestly Significant Difference (HSD) post-hoc test are applied on aggregated data.

5 Results

The experiment sample is composed by 46 subjects. 31 of them are surgeons and 15 residents with different background. Fig. 6 shows the composition of the sample by specialization (Fig. 6.a), experience in laparoscopy (Fig. 6.b) and experience with surgical simulators (Fig. 6.c) or in robotic surgery (Fig. 6.d).

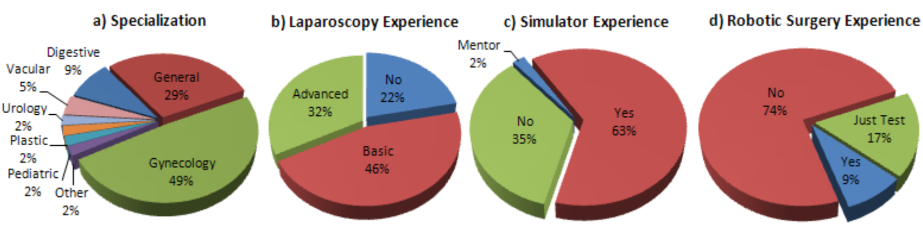

Fig. 6. Statistics of experiment population

At each temporal step k the system logs the position of the TCP $\mathbf{x}(k)$ and coordinates of the goal point $\mathbf{g}(k)$ on the trajectory, in addition, when the user passes through a trajectory point p the system stores the elapsed time since the beginning of the trial t_p. Since each trial has a different completion time and thus a different amount of sampled data, values logged during each trial have been aggregated to ensure the comparability of the results. For the i-th trajectory point of coordinates $\mathbf{p}_i$ the cumulative error e_i and the latency l_i are defined:

$$e_i = \sum_{j|\mathbf{p}_i=\mathbf{g}(j)} \|\mathbf{x}(j) - \mathbf{p}_i\|_1 \quad (3)$$

$$l_i = t_i - t_{1-i} \quad (4)$$

i.e. the total distance covered (measured with the Manhattan distance) and the time spent to move from the point to the next one.

The proposed experimental design includes two factors: virtual fixtures (6 levels, one for each VF plus the VF free scenario) and the trial number (8 levels: one for each VF free trial in the sequence). The analysis of the performance trend of the subjects evaluated during the whole experiment by the VF free trials and among each VF trials provides different results for the error measure and for the latency measure. The mean values of the cumulative error and the latency are shown in Fig. 7 and Fig. 8 respectively.

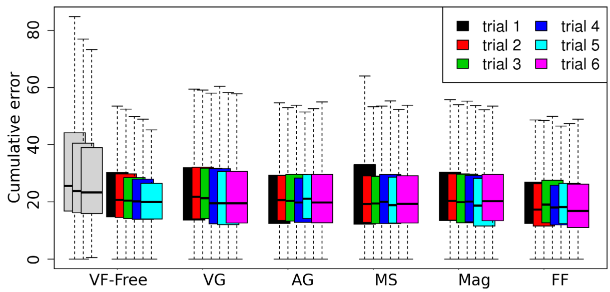

Fig. 7. Mean value and interquartile ranges (lower bound, first and third quartile, upper bound) for the cumulative error along trials

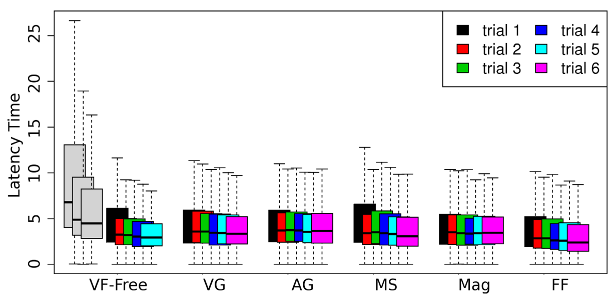

Fig. 8. Mean value and interquartile ranges (lower bound, first and third quartile, upper bound) for the latency along trials

The trend of the cumulative error for the VF free trials shows a considerable gap between the third and the fourth repetition. The gap between the trials then decreases significantly. The step in the cumulative error trend appears in correspondence with the first block of VF assisted trials after the three initial VF free repetitions. These results lead to the conclusion that the introduction of any virtual fixture strongly affects the user performance and that this effects continues even when the support of the VF is disabled. This analysis does not allow to identify the most effective VF, since their random presentation order drops the effect of VF factor. The trend of latency plots does not allow to assume any positive effect of VFs on the completion time. Together with the considerations provided for the cumulative error, this suggests that VFs are effective in increasing subject's accuracy but they do not increase the speed of user's motion.

RM-ANOVA applied to data collected during the VF assisted trials shows the statistical significance of the VF factor with a value of $F_{(5,98131)} = 35.030$, $p < 0.001$ for the cumulative error analysis and a value of $F_{(5,98131)} = 44.099$, $p < 0.001$ for the latency analysis. The effect of the trial factor is also significant for cumulative error $F_{(7,98131)} = 22.871$, $p < 0.001$ and latency $F_{(7,98131)} = 87.344$, $p < 0.001$. This proves that different VFs provide different effect on user performance. Tukey HSD test shows that FF is the most effective VF in reducing cumulative error but its effect is not significantly different from AG and MS. The same test on latency values shows that completion time is improved by Mag and that its effect is not significantly different from the one of AG.

6 Conclusions and Future Work

The work presented in this paper analyzes the effects of VFs on the learning of basic surgical skills in virtual training environments. Five different VFs have been integrated in a surgical simulator and proposed as training supports to surgeons and residents for a trajectory following task.

Data collected during the analysis highlight the positive influence of VFs on subjects' learning and allow the evaluation of the effectiveness of the proposed VFs in terms of cumulative error and latency reduction. The difference between the effects of VFs has been assessed by a RM-ANOVA. FF proves to be the most effective fixture in reducing the cumulative error, whereas Mag provides the strongest effect on the latency. Since in most surgical tasks accuracy has to be preferred over speed the outcome of this analysis suggests to focus training assistance on the FF and on the haptic channel on which FF relies. In addition, the positive effect of AG on both the evaluation parameters indicates that the audio channel can be effectively used to convey information to the user.

The proposed analysis will be extended to evaluate the performance of the subjects in presence of occlusions along the trajectory, thanks to the heterogeneous composition of the sample we will be able to evaluate the effect of subjects expertise on the performance. Moreover we will verify the effect of combining multiple VFs to increase the overall effect and evaluate the need for developing additional VFs to fit other tasks peculiarities.

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