Visuo-haptic feedback for 1-D Guidance in laparoscopic surgery

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Abstract— **Due mainly to drastically shortened recovery times and lower overall cost, minimally invasive surgery (MIS) is growing standard for many surgical interventions. However, associated loss of visual depth perception, difficult hand-eye coordination and distorted haptic sensation tend to complicate this task for the surgeon.**

In this paper, we explore the potential of simple visual, haptic or combined visual and haptic cues for intuitively assisting surgeons in moving their instrument tip within a predefined 3-D plane. 23 subjects carried out trajectory following tasks within a plane under provision of 9 different combinations of visual and haptic guidance feedback. Evaluated forms of haptic feedback encompassed both tactile cues and kinaesthetic feedback using soft virtual fixtures.

Results show clear superiority of soft guidance virtual fixtures over other forms of feedback, leading to performance levels above those obtained in open surgery. However, promising results for the use of cutaneous vibrotactile feedback are also obtained, with potential for integration in MIS tool handles.

I. INTRODUCTION

Laparoscopic surgery encompasses minimally invasive surgeries (MIS) on the abdominal region, and is characterized by the use of thin elongated instruments inserted into the body via trocars while the operating site is monitored using an endoscope. MIS has become standard for many surgical procedures as it has great advantages over open surgery in terms of cosmetic results, patient recovery time and overall procedure cost to name a few ([7],[8],[9]).

In the field of MIS and robotically assisted minimally invasive surgery (RMIS), haptic feedback technologies are receiving growing attention in particular as an option to restore haptic sensation in teleoperated surgery ([10],[11],[12]). Indeed, in MIS, the operating conditions lead to degradation and distortion of haptic perception for the surgeon ([13],[14],[15]), and in RMIS, teleoperation often leads to complete loss of haptic perception of the operating field.

Based on this observation, a first natural avenue for exploring possible improvements to MIS techniques and tools lies in the idea of restoring lost functional haptic perception. Another approach lies in exploiting the under-used haptic modality to convey additional useful information, by using tactile ([2],[3]) or kinaesthetic (force feedback) stimuli.

*This work was supported by French state funds managed by the ANR within the Investissements d'Avenir programme (Labex CAMI) under reference ANR-11-LABX-0004.

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Our work focusses on this second axis : We seek to provide the surgeon with guidance information through the haptic modality instead of the saturated visual and auditory modalities. Indeed, among others, [23], [24] and [27] have shown that significant improvements to performance can be obtained when information is more evenly distributed throughout various sensory modalities or presented in a congruent multi-modal fashion.

When trying to convey useful information through the haptic channel, the idea of haptic guidance has appeared in several domains such as vehicle ([16], [18]) and pedestrian ([17], [28]) navigation, fast gesture guidance [1], gesture guidance for rehabilitation ([19],[20]), aiming at targets [21] and gesture guidance for learning complex gestures (e.g. music [22], [5]).

In the following, we present an experiment aimed at evaluating the respective contributions of haptic feedback (tactile and kinaesthetic), visual feedback, and their combinations in guiding a user's tool towards a target plane during a trajectory following task in said plane.

In the context of a laparoscopic hepatectomy, the surgeon must delineate a plane crossing the liver along which the organ is then to be resected. The clinical quality of a hepatectomy is judged among other things by the fact that as little healthy tissue as possible is resected while all pathological tissue is removed. This supposes correct navigation of the instrument tip towards the defined plane while cutting, which can be a tricky task even for experienced surgeons. This has motivated the choice of our experimental set-up for these first experiments.

We focus on vibrotactile and visual stimuli as the required displays are now state-of-the-art and certain findings ([25]) indicating these stimuli lead to fastest responses in guidance tasks. Kinaesthetic feedback using virtual fixtures is already state-of-the-art in certain forms of surgery and there is growing interest in finding applications to surgery on moving and deformable organs.

Subjects are asked to follow trajectories lying in a plane using the tip of a surgical tool in a laparoscopic setting under provision of 9 different combinations of visual and haptic feedback indicating their relative position to the plane. The quality and speed of the executed task are then evaluated. Performances of two forms of vibrotactile feedback, visual feedback, soft guidance virtual fixtures and their combinations are compared amongst each other and against reference performances in open surgery and MIS settings.

Section II details the experiment. The results are then reported in section III, and discussed in section IV.

II. MATERIALS AND METHODS

A. Experimental set-up

23 healthy subjects (16 male, 7 female, all right-handed with no medical background or previous laparoscopic experience) were placed before a laparoscopic training simulator (Endosim LaproTrain^{TM}) shown in figure 1 equipped with a board supporting three vertical pegs. The peg tips form a steeply inclined plane, as shown in figure 2. Each tip is equipped with a pin connected to an Arduino Uno board, allowing for detection of contact between the instrument tip and a given pin.

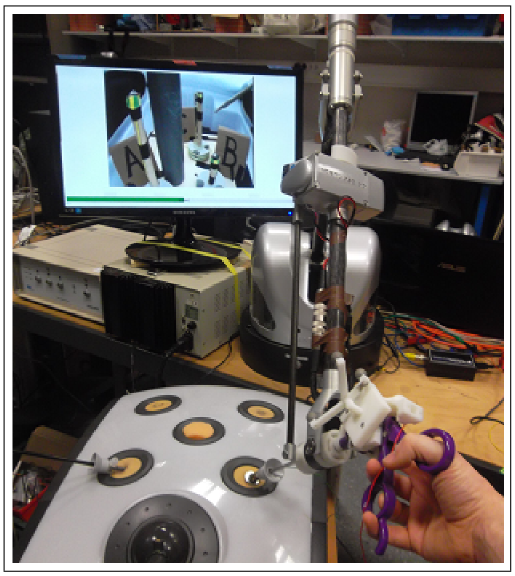

Fig. 1. Subject point of view for laparoscopic surgery task with kinaesthetic and visual feedback. On the bottom right, the subject's hand manipulates the laparoscopic tool fitted with optical tracking markers. A haptic interface is also attached to the shaft of the tool just below the handle and acts as a co-manipulator. The subject is presented the view from the endoscope on the screen seen at the top left of the image.

The subjects were asked to follow arbitrary trajectories between pins, starting at a given pin and always returning to it via both other pins. The main objective for the subject was to maintain the instrument tip within the target plane, i.e. to minimize normal deviation to the plane while following the trajectory. The secondary objective was to minimize the time to complete the task, without however sacrificing accuracy performance.

The instruments are tracked using an NDI Polaris^{TM}optical tracking system using markers mounted on the instruments (see figure 1). 3D positional data for the instrument tip, the computed associated normal deviation from the plane and associated timestamps are acquired via a PC with an average acquisition frequency of 58Hz.

B. Forms of feedback provided

When provided with feedback, the users were informed of their normal deviation to the plane in various manners. Only this 1-dimensional information was provided (distance to the closest point in the target plane), leaving the trajectory following task within the plane entirely up to the subject.

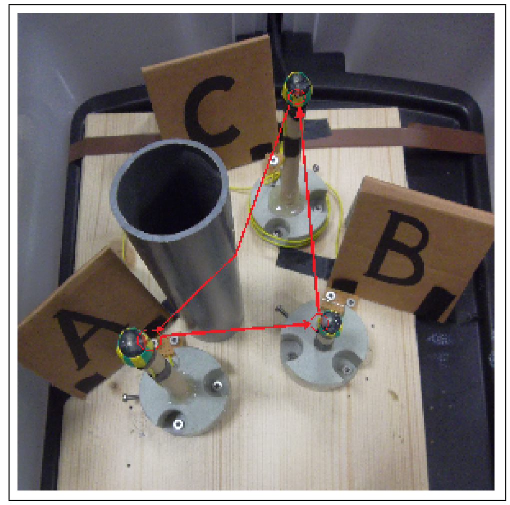

Fig. 2. View from above the inside of the laparoscopic training simulator. The red circles highlight the electrical contacts on each of the three pegs and the arrows show an example of trajectory to be followed. An obstacle is placed on the [AC] trajectory in order to further complicate the task and assess the impact of the provided feedback when trajectories became less intuitive.

In laparoscopic settings, we consider conditions as being "without feedback" when the user is only presented with the endoscopic image.

1) Cutaneous vibrotactile feedback: Cutaneous vibrotactile feedback was provided to the user via an eccentric rotating mass (ERM) motor (Precision microdrives^{TM}Pico Vibe 307-100 [30]) strapped to the inner side of the index finger holding the instrument (see figure 3). This placement is interesting in the context of integration of vibrotactile feedback to the handle of serial co-manipulators for laparoscopic surgery.

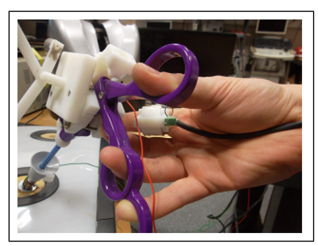

Fig. 3. ERM vibrating motor attached to the subject's hand

Two forms of vibrotactile feedback were implemented, continuous proportional feedback and threshold feedback.

- Continuous proportional feedback was provided as a permanent vibration whose intensity varied in a linear fashion from 0g when exactly on target (based on results obtained in [21], the absence of vibrotactile feedback when on target is preferable in terms of comfort and achieved performance) to the maximum intensity (i.e. 7g) when deviating by 30mm or more.
- In threshold vibrotactile feedback, the user was only informed of the fact that he was crossing one of the following deviation magnitude thresholds : [2mm ; 4mm], [15mm - 17mm], [>30mm]. Vibration was provided at low (0.3g), medium (4.5g) and maximum (7g) intensity

levels respectively, and the motor vibrated as long as the user was within these thresholds, regardless of the direction of the movement being towards or away from the plane. The middle threshold was selected simply as being the midpoint between the target and the maximum observed deviations during pilot tests.

As with ERM motors, vibration amplitude and frequency are linked, the frequency of the vibrotactile feedback varied almost linearly between 25Hz and 260Hz, see [30] for detailed information on the amplitude/voltage and frequency/voltage relationships for the employed ERM motor.

2) Visual Feedback: Visual feedback cues were provided in the form of a bar-graph placed horizontally beneath the endoscopic image (see figure 1). The numeric value of the magnitude of the deviation rounded to the closest mm was also overlaid on the bar-graph. The bar-graph was centred and green when deviations were in the [-4 mm ; 4 mm] range. The colour changed to yellow in the [4mm ; 15mm] deviation magnitude range and to orange in the [15mm ; 30mm] range. Beyond 30mm deviation magnitude the bar-graph became red. The height of the bar-graph also provided continuous information on the magnitude of the deviation and its increase or decrease.

3) Virtual fixtures (kinaesthetic feedback): Soft guidance virtual fixtures were implemented using a Haption Virtuose 6D™haptic interface set up as a parallel co-manipulator, i.e. the haptic interface applied forces to the instrument just beneath the handle held by the user in order to guide the user back towards the plane. These forces were calculated as per (1) in order for the effect achieved to be that of a virtual spring (k = 400N/m) attached between the instrument tip and the plane.

$$\vec{F_{wrist}} = l_{out}/l_{in} \cdot (-k \cdot \vec{n} \cdot d) \quad (1)$$

where l_{out} and l_{in} respectively denote the lengths of instrument shaft inside and outside of the point of insertion, d is the current deviation from the plane and $\vec{n}$ is the plane's normal vector.

The choice of making these virtual fixtures "soft", i.e. leaving a margin for deviation around the target, stems from the clinical need to leave the surgeon in control of the action in the case where minor deviations from the pre-operative plan may be necessary. Also, we wish to keep the virtual fixtures mainly informative for sake of comparison with the other forms of feedback.

4) Feedback thresholds: Pilot tests showed that deviations around 30mm were the maximum deviations usually obtained when performing the task in a laparoscopic setting with no feedback, hence the choice of this value as the upper threshold. They also showed the lower threshold for perceiving clear vibrotactile indications of deviation as being between 2mm and 4mm, which we used as the basis for setting the first colour change of the bar-graph used for visual feedback and lower threshold for the second form of vibrotactile feedback. The middle threshold for threshold vibrotactile feedback was also selected as the threshold for the second colour change of the bar-graph. The stiffness for kinaesthetic feedback was selected during pilot trials in order for the detection thresholds of the kinaesthetic cues to match those of the vibrotactile cues.

C. Experimental conditions

The experiment encompassed 11 conditions grouped into three blocks : reference conditions (RC), Visual-Tactile conditions (VT) and Visual-Kinaesthetic conditions (VK). Subjects always started with the RC block, the order between VT and VK blocks was randomly selected, and the order of conditions within each block was also randomized. The abbreviations used are summarized in table I below.

1) Reference block: Three conditions were used as reference measurements :

- Open surgery (RC-O)
  In this condition, subjects were placed before the LaproTrain™with the cover removed so as to simulate an open surgery situation. The instrument used was a standard needle-holder fitted with an electrical contact on the tip for contacting the pegs and markers for optical tracking.
- Laparoscopic surgery (RC-L)
  In this condition, the lid was placed back on the LaproTrain and subjects manipulated a standard laparoscopic forceps also fitted with electrical contact at the tip and optical tracking markers. The instrument was inserted through a 5mm trocar and the endoscope image shown on a 24" screen placed roughly at the height of the subjects head directly in front of them. This basic set-up was kept for all following conditions.
- Laparoscopic surgery with visual feedback (RC-LV)
  In this condition, subjects were provided visual feedback in the form of a bar-graph as previously described. We consider this condition a reference as this work focusses mainly on haptic feedback, and this condition can serve as a reference for evaluating the added benefit of visuo-haptic feedback.

2) Visual-Tactile block: This block comprised four combinations of vibrotactile and visual feedback :

- Continuous vibrotactile feedback alone (VT-C)
  Keeping the basic set-up from RC-L, subjects were provided continuous proportional vibrotactile feedback as described above.
- Continuous vibrotactile + Visual feedback (VT-CV)
  This condition is identical to VT-C, with the addition of visual feedback as described above.
- Threshold vibrotactile feedback alone (VT-T)
  This condition differs from VT-C only in the fact that the vibrotactile cues changed from continuous proportional feedback to threshold feedback.
- Threshold vibrotactile + Visual feedback (VT-CT)
  This condition is identical to VT-T, with the addition of visual feedback as described above.

3) Visual-Kinaesthetic block: This block comprised four combinations of kinaesthetic and visual feedback :

- Inactive haptic interface + No visual feedback (VK-I)

TABLE I

SUMMARY OF ABBREVIATIONS USED FOR THE EXPERIMENTAL CONDITIONS

Abbreviation	Experimental condition
Reference block	
RC-O	Reference condition : Open Surgery
RC-L	Reference condition : Laparoscopy
RC-LV	Reference condition : Laparoscopy with added visual feedback
Vibrotactile feedback block	
VT-C	Continuous proportional vibrotactile feedback
VT-CV	Continuous proportional vibrotactile feedback with added visual feedback
VT-T	Threshold vibrotactile feedback
VT-TV	Threshold vibrotactile feedback with added visual feedback
Kinesthetic feedback block	
VK-I	Inactive haptic interface
VK-IV	Inactive haptic interface with added visual feedback
VK-VF	Soft guidance virtual fixtures
VK-VFV	Soft guidance virtual fixtures with added visual feedback

For this condition, a Virtuose 6D (Haption) haptic interface is attached to the instrument just below the handle. However, the haptic interface does not apply any forces on the instrument and does not compensate its own weight. The objective was to assess to what extent this passive parallel co-manipulation set-up affected subject strategies and performance compared to RC-L.

– Inactive haptic interface + Visual feedback (VK-IV)
This condition had an identical set-up to VK-I, however the subjects were provided visual feedback in the form of a bar-graph. This allows a comparison to RC-LV similar to that described between VK-I and RC-L.
– Soft guidance virtual fixtures alone (VK-VF)
This condition has an identical set-up to VK-L, however this time the haptic interface was active and applied forces so as to guide the user back towards the target plane in the event of deviation, as described above.
– Soft guidance virtual fixtures + Visual feedback (VK-VFV)
This condition is identical to VK-VF, with the addition of visual feedback.

In order to complete each of these conditions, the subjects were asked to follow 5 randomly defined trajectories in a row. For each condition, subjects were informed of the nature of the feedback they would receive. They were instructed to try and best use all forms of feedback made available, however the choice of strategy for using the feedback was left up to the subject. This seems reasonable in terms of generalizability to the surgical context, where surgeons are aware of the information they can obtain from their various tools prior to their use. By not imposing the strategy for using the available information, we hope to obtain some information on the intuitiveness and ergonomics of the various types of feedback.

In a surgical context, the surgeons main objective is to be sufficiently precise in his gestures so as to ensure the required quality of the surgical intervention while minimizing operation time. For both clinical and economic reasons, we expect that depending on the available information (haptic and/or visual), subjects should be able to more or less optimize their speed/accuracy trade-off in the performance of this task.

III. RESULTS

In this section we present the results for time and precision criteria for the various conditions. One-way ANOVAs were performed to assess the statistical significance of all observed differences between conditions.

A. *Times to complete the task (TCT)*

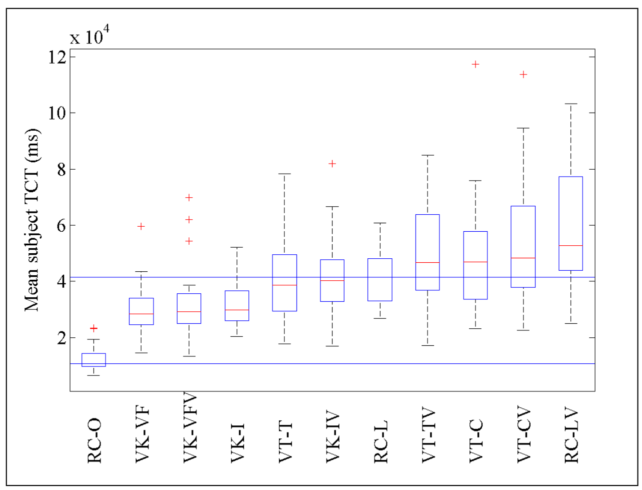

Fig. 4. Mean subject TCT

Figure 4 shows the distribution of the mean TCT for each subject over all 11 conditions. A clear increase of the TCT is notable between conditions RC-O and RC-L (strong significance with $p < 0.01$). Contrary to our hypothesis, most feedbacks lead to increased TCT compared to RC-L, however the observed differences are not statistically significant. Exceptions to this are conditions VK-VF, VK-VFV and VK-I which on average take the subjects 30s to complete a trajectory against the 40s necessary in condition RC-L (strongly significant difference with $p < 0.01$), and condition VT-T, which has slightly shorter TCTs than the reference RC-L but not in a significant manner.

Surprisingly enough, conditions VK-I and VK-IV show an increase in speed for accomplishing the task compared to RC-L and RC-LV, despite our initial assumption that the inactive haptic interface would tend to hinder movement. This could point to either a stabilization effect obtained by the robot's viscosity and the fact that the tool is maintained in two places - at the trocar and at the robot wrist. It could also be due to the psychological effect of the user becoming more confident and thus executing movements faster when co-manipulating the instrument. It should be noted that the respective differences in TCT observed between RC-L and VK-I, and RC-LV and VK-IV are both strongly significant with $p < 0.01$.

It is interesting to note the fact that addition of visual feedback to any modality increases the mean TCT (significantly for RC-L, VK-I, and VT-T ($p < 0.01$)).

B. Relative time spent on target (ToT)

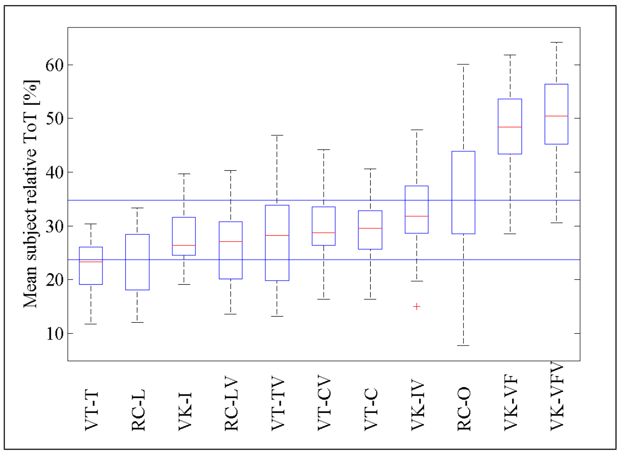

Fig. 5. Relative ToT (deviation < 1mm) as a percentage of the TCT

Figure 5 shows the times spent at a sufficiently low deviation from the plane to be considered on target (i.e. at deviations below 1mm) relative to the TCT. The percentage of the path length travelled on target by the instrument tip relative to the total path length travelled shows almost identical results with the exception of the RC-O condition which performs second worst after the RC-L condition. This is most likely due to the fact that the freedom of movement in the RC-O condition allowed users to rapidly travel between pegs, leading to slightly increased deviations being reached during movements at higher speeds.

Again, RC-L shows a significant degradation of performance when compared to RC-O (drop from 35% time on target to 24% time on target (significant with $p < 0.01$)). Here however, we see that all feedbacks improve performance over the RC-L reference condition, with the exception of VT-T which performs slightly worse but not significantly. Conditions VT-C and VT-TV bring the time on target back up around 28% (significant with $p < 0.01$), as does VT-CV (significant with $p < 0.05$).

Matching the observation for TCT, conditions VK-I and VK-IV both significantly improve ToT over their counterparts RC-L and RC-LV (+3% and +4% respectively($p < 0.01$)). This hints to an actual beneficial effect of the inactive haptic interface as better performance is achieved both for the time and precision criteria.

The bad performance of VT-T seems to indicate the ineffectiveness of this feedback scheme by itself, as for both time and precision criteria, performances do not significantly differ from condition RC-L. The observed non-significant increase in precision between RC-LV and VT-TV leads us to believe that the performance obtained with VT-TV is mainly if not entirely due to the visual feedback.

Regarding ToT, VT-C leads to significantly better performances over RC-L (+6% ($p < 0.01$)) and shows slightly better results than VT-CV, though the observed difference is not significant. This hints to the effectiveness of VT-C in terms of precision, and to the fact that presenting the deviation information redundantly via the haptic and visual channels has no visible advantage.

It should be noted that no feedback condition except KF-VF and KF-VFV leads to performances equal or above those obtained in RC-O. Both conditions KF-VF and KF-VFV are clearly set apart from the other conditions ($p < 0.01$), with approx. 50% time spent on target against only 24% for the reference laparoscopic condition, 35% for the reference open condition and 30% for the best performing vibrotactile feedback condition (VT-C).

C. Deviation amplitudes

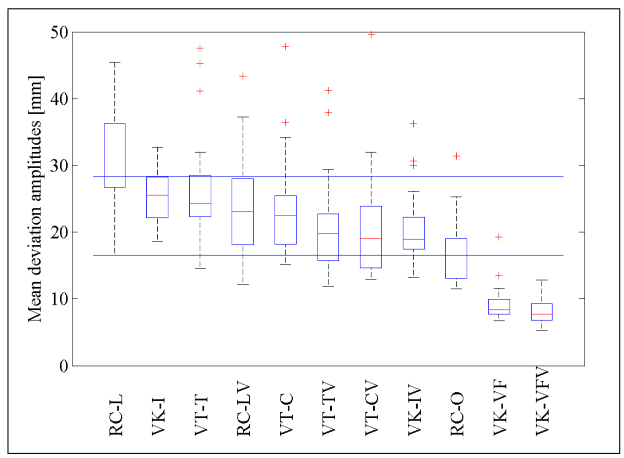

Fig. 6. Mean deviation amplitudes (Maximum deviation above the plane + Maximum deviation below the plane) for each condition

Another important measure for clinical relevance is the maximum error in any given condition. When observing mean deviation amplitudes (i.e. the sum of maximum positive and negative deviations from the plane) as shown in figure 6, we confirm previous results.

As seen in figure6, the RC-L condition shows the greatest degradation in performance (+6mm increase in mean maximum deviations and +10mm increase in deviation amplitude (both strongly significant with $p < 0.01$)) when compared to the RC-O condition. Added feedback tends to improve over this degradation without ever reaching the performance in RC-O except for conditions VK-VF and VK-VFV, which both reduce maximum deviations and deviation amplitudes by about half compared to RC-O (strongly significant with $p < 0.01$).

When it comes to peak deviations, the addition of visual feedback to RC-L and VT-C seems to show greater improvements than when considering the performance on target. VT-CV shows a -3mm decrease in peak deviations and -5mm decrease in deviation amplitudes compared to VT-C, however these differences are still not statistically significant. This would hint towards an added benefit from congruent multimodal feedback in avoiding too high peak errors, however the lack of statistical significance does not allow us to push conclusions further.

Overall, the addition of visual feedback to VK-VF also improves performance but not significantly.

D. Analysis of the speed-accuracy trade-off

To get a clearer idea of the effect of various feedback conditions on the speed-accuracy trade-off used by the subjects, we analyse a score defined as the multiplication of TCT and deviation amplitude, in [mm.ms], for the various conditions as shown in figure 7.

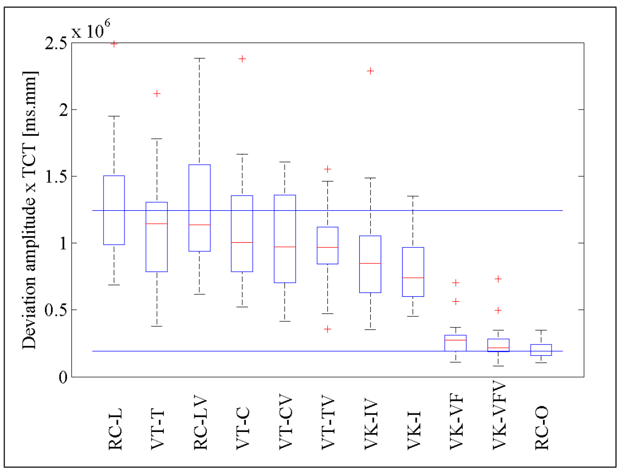

Fig. 7. Evaluation of the speed-accuracy trade-off for the various conditions

Defined this way, a condition scores best when its (deviation amplitude · TCT) is lowest. This graph again shows the greatest degradation in performance occurring between RC-O and RC-L, highlighting the simultaneous increase of TCT and deviation amplitudes (strongly significant with $p < 0.01$).

The RC-O condition stands out as having the best performance here, significantly outperforming VK-VF ($p < 0.05$) but not VK-VFV. This reflects the fact the freedom of movement in RC-O allows for very short TCTs while staying in deviation ranges comparable to VK-VF.

Conditions VK-I and VK-IV stand out particularly clearly here, significantly outperforming RC-L and RC-LV ($p < 0.05$) . The stabilisation introduced by the passive haptic interface seems to have a beneficial impact on the speed-accuracy trade-off performed by subjects.

Finally, VT-CV leads to significantly better performances than RC-LV ($p < 0.05$), once again hinting at a possible beneficial effect of congruent multimodal feedback in avoiding larger deviations when moving at similar speeds.

IV. Discussion

As explained previously, the main criteria compared in these experiments are precision criteria and times to complete trajectories. The objectives as given to the subjects were to prioritize precision over fast execution when performing the task, and it was expected that the various ergonomics and levels of available information would affect the speed-accuracy trade-off made by subjects in each condition.

A. Drop in performance between RC-O and RC-L

As expected, the RC-L condition shows the greatest degradation of performance when compared to RC-O. Both TCTs and precision criteria show a notable drop in performance, indicating that laparoscopic conditions do not only change the user's speed-accuracy trade-off, but actually create a hindrance to the execution of the task. We believe this is due to the combined effects of loss of depth perception, complicated hand-eye coordination, use of long instruments and distorted haptic sensation due to friction in the trocar and variations in the stiffness of the trocar insertion depending on insertion angle and depth.

B. Effectiveness of providing feedback

For all criteria analysed, the presence of any type of feedback improved performance in terms of precision when compared to RC-L. Analysis of significance of these improvements leads us to conclude that all feedbacks with the exception of VT-T improve the quality of the execution of the task. When looking at TCTs however, it seems that added feedback tends to slow down the execution of the task, with the exceptions of VT-T, VK-VF and VK-VFV. We believe VT-T is set apart here as it is actually comparable to RC-L in the sense that the vibrotactile feedback seems to be largely ineffective in this form and was thus likely mostly ignored by the users.

C. Best performance obtained with virtual fixtures

The significantly improved precision of VK-VF and VK-VFV coupled with significantly reduced TCTs when compared to other feedback conditions confirms our hypothesis that soft guidance virtual fixtures go beyond the scope of simple informative feedback and actually provide a safe framework within which the user is comfortable in rapidly executing the task while only worrying about perfecting certain aspects of the movement. Thanks to this, precision performances in VK-VF and VK-VFV are even better than those obtained in RC-O.

The addition of visual feedback to VK-VF has non-significant advantages in terms of accuracy performance and leads to a non-significant degradation of the TCT. Therefore we cannot conclude that adding visual feedback to guidance virtual fixtures is interesting from the point of performance. However, from an ergonomics point of view, it is interesting to note that users all reported that the addition of visual feedback increased their comfort with the task as it confirmed the quality of the assistance they were receiving from the haptic interface.

D. *Effectiveness of vibrotactile feedback*

For all vibrotactile feedbacks except VT-T, improvements over RC-L vary without ever reaching the level of performance obtained in RC-O for both precision and TCT. TCTs are generally increased when vibrotactile feedback is provided, reflecting the modified subject strategies to use the provided information. However, these increases are limited compared to those generated by visual feedback as provided in RC-LV. When dealing only with precision criteria, VT-C stands out as a particularly interesting form of feedback, bringing performance levels close to RC-O.

E. *Effectiveness of visual feedback*

The addition of visual feedback usually results in longer TCTs when compared to the corresponding condition without visual feedback. Furthermore, TCTs in RC-LV are longer than for all conditions from the VT block.

This can be due either to the overloading of the visual modality or to the fact that with this precise form of feedback, users tend to be more careful and therefore slower, or a combination of both. As accuracy performances tend to increase (not always significantly) without significantly increasing TCTs under provision of visual feedback, we hypothesize that the observed slowing is not only due to the overloaded visual modality but actually reflects a modification of the subjects strategy towards being more careful.

The addition of visual feedback to provide combined visual and tactile feedback yielded mixed results. When considering the precision "on target" and TCTs, the added visual feedback seemed to make no significant difference. However, it would seem that visual feedback becomes effective in avoiding larger deviations, which may prove quite valuable in particular when considering forms of feedback where movement is not constrained (i.e. all conditions from the VT block).

F. *Ineffectiveness of VT-T*

The threshold vibrotactile feedback showed no significant improvements over the RC-L condition, leading us to believe that it is ineffective on its own. This is probably due to the fact that the provided information lacks sufficient components to allow spatial orientation necessary for corrective movements.

V. CONCLUSIONS

This work has revealed the beneficial effect of added feedback to compensate for the perceptual limitations induced by the characteristics of the laparoscopic surgery setting. Visual cues, vibrotactile cues, kinaesthetic cues in the form of soft guidance virtual fixtures and their combinations were all compared between each other and against reference performances in open surgery and MIS settings. These findings stay in accordance with previous findings on visual feedback in tool aiming tasks ([4], [6]) and the use of vibrotactile feedback ([3], [2], [26]), in that the addition of any form of feedback indicating a deviation from the desired position reduced the amount and amplitudes of deviations over comparable distances travelled and times spent accomplishing the tasks.

Properly implemented feedback cues providing comprehensible information to the user notably improves performance in a guidance task. Therefore we believe that inclusion of such feedback based on pre-operative planning in surgical procedures could potentially serve to ensure greater safety, reduce operating times and improve surgeon comfort during procedures.

Furthermore, we show that properly implemented cutaneous vibrotactile feedback can actually achieve performances above those obtained using visual feedback. This confirms our hypothesis that the use of the haptic modality can serve to provide useful and effective information to the subject without overloading the visual modality. This result is particularly encouraging considering the potential for integrating vibrotactile feedback to surgical instrument tool handles.

Finally, the comparison with soft guidance virtual fixtures shows a clear superiority of these compared to all other forms of feedback. Performances achieved are even better than reference performances in open surgery. This should however be moderated by the two following considerations :

First, virtual fixtures require a set-up for teleoperation or parallel co-manipulation, raising potential issues of clutter and significant added cost for applications to the operating room. And second, virtual fixtures leave little room for actions outside the predefined target range. Even soft guidance virtual fixtures cannot be ignored in the event of the necessity to deviate from the planned target, raising issues of safety and complexity of implementation.

Concerning all forms of feedback, an open question remains as to the advantages they would provide for trained surgeons. Previous works have shown that haptic perception in laparoscopic settings improves with training [29], and trained surgeons would be less prone to making large mistakes in conditions with purely visual or tactile feedback due to their training.

Due to the promising nature of these initial results concerning continuous vibrotactile feedback, future work will focus on evaluating the benefit of adding directional information to this modality and refining the way in which the information is displayed. Evaluation should then take place for more complex guidance tasks (2D and 3D trajectories). Finally, we also aim to further improve the comfort of the vibrotactile cues and aim to integrate the actuators into the handle of a laparoscopic instrument in order to assess potentially clinically valid benefits in experiments with surgeons and interns.

A further interesting result was obtained when comparing performances between a standard laparoscopic setting and the use of an inactive haptic interface as parallel co-manipulator. It would seem that the stabilization effect obtained by the support of the instrument at two points instead of only at the trocar coupled with the viscosity of the robot tended to improve performances in the given task. Questions that remains to be addressed are whether or not these improvements are repeatable in non-novice populations and on more complex guidance tasks. If so, the exploration of passive stabilization systems for improving laparoscopic surgery performance could be of interest.

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