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Abstract Minimally invasive surgery (MIS) is gaining widespread acceptance thanks to benefits obtained for the patient, most notably shorter recovery times and post-operative pain as well as better cosmetics and lower overall cost. Surgeons, however, face new challenges due to limited dexterity and degraded perception of the operative field. In particular, visual and haptic perception are disturbed through loss of visual depth cues, complicated hand-eye coordination and distorted haptic sensation.

Given this situation, we propose concepts for assisting surgeons in the execution of their gestures by providing relevant information allowing them to correct errors occurring due to these perceptual limitations. In our experiments, we focus on the problem of guiding the tip of a laparoscopic instrument along a predefined 3-D target plane within a patient.

In the experiment detailed here, 11 novice subjects carried out trajectory following tasks within a plane under provision of 4 different combinations of visual and vibrotactile feedback. The aim is to confirm results from a previous experiment in which we compared visual, cutaneous vibrotactile and kinaesthetic feedbacks for assisting a user in keeping the tip of their instrument on target. We obtained encouraging results and revealed strengths and weaknesses for the forms of feedback studied, however we could not rule out bias from potential learning effects due to limitations in the experimental design.

Through the fully randomized experiments presented here, we confirm that visual and tactile feedback significantly improve the quality of gestures whether alone or in combination, with multi-modal feedback significantly improving performance over the use of individual feedbacks.

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1 Introduction

Shorter hospital stays and convalescence ([18]), lower cost ([11]) and better patient outcomes ([18]) have popularized minimally invasive surgery (MIS) for many surgical interventions. However, the ergonomics of MIS incur limitations for the surgeon ([24]) which have sometimes been shown to negatively affect surgical performance ([6], [16]).

We hypothesize that the perceptual limitations inherent to MIS could be in part overcome by feeding back relevant information on the state of the surgical instrument and its interaction with surgical targets to the surgeon during the operation using augmented reality. The experiments presented in this paper focus on the problem of assisting the surgeon in precisely guiding a surgical instrument tip within the patient's abdomen. The idea is to acquire the position of the instrument tip in space and to feed back the minimum amount of information relevant to the surgical task in order for the surgeon to efficiently correct for any deviation from the target.

Both visual and vibrotactile feedback ([1]) as well as kinaesthetic feedback ([10]) have been considered as means for improving performance in gesture guidance and learning. Haptic guidance has been widely explored in rehabilitation scenarios (e.g. [5]), teaching of complex gestures (e.g. musical instrument playing ([12], [14]) or sports ([21]). An conclusion often reached is that congruent visual and vibrotactile feedback improves the quality of gestures, whereby vibrotactile feedback alone allows for faster responses than visual feedback, probably because of the lower induced cognitive load ([19], [21]). Vibrotactile cues for guidance have also been explored for pedestrian ([8]) and vehicle ([7], [22]) navigation, concluding that tactile feedback functions best in situations with high visual cognitive load and concurrent tasks.

Haptic feedback for surgical tool navigation has been explored mostly in the context of RMIS, using mainly kinaesthetic feedback ([17], [9]). However, tactile feedback has also been considered as an viable solution, either for co-manipulation ([20], [25]) or as a form of sensory substitution. Bluteau et al.[2] study the use of vibrotactile cues for guiding a tool along a 3D trajectory in traditional (open) computer assisted-surgery (CAS). Similar work by Hansen et al.[13] investigated such forms of feedback for improving surgical navigation during resection tasks. Brell et al. ([3]) review work and design considerations for tactile feedback to augment surgical gestures based on preoperative information, noting that tactile feedback is a promising alternative to visual guidance as the cues are private, intuitive and can easily code complex spatial information. While purely visual feedback yields lower errors than purely tactile feedback, it also significantly prolongs the time to complete the task (TCT). They achieve best results through combined visual and tactile feedback, with extremely low error rates although TCTs are longer than for tactile feedback alone.

In the following, we present an experiment aimed at evaluating the respective contributions of cutaneous vibrotactile feedback, visual feedback, and their combinations in guiding a user's tool towards a target plane during a trajectory following task within said plane. Subjects are asked to follow trajectories lying in a 3D inclined plane using the tip of a laparoscopic surgical tool under provision of 6 different combinations of visual and haptic feedback on their relative position to the plane. The quality and speed of the executed task are then evaluated. Performances of cutaneous vibrotactile feedback, visual feedback, and their combinations are compared amongst each other and against reference performances in unassisted MIS.

Section 2 describes the experimental hardware and set-up. Section 3 then details the experimental protocol, starting with a recap of our previous experiments and continuing with the experiments at the core of this paper. In section 4, we compare our newly obtained quantitative performance data with those from our previous experiments as well as exploratory data obtained from one surgical intern. Furthermore, we present a qualitative evaluation of user perception on the use of various forms of feedback. Finally, conclusions and prospects for further work are presented in sections 5 and 6.

2 Materials

Subjects were placed in front of a laparoscopic trainer (Endosim LaproTrain™, shown on the right in fig. 1) and manipulated laparoscopic forceps through a trocar while observing the endoscopic image on a 24" screen placed in front of them. Three different sized pegs (A,B and C respectively) were set up vertically within the trainer so that their tips formed a steeply inclined plane similar to resection plane for a hepatectomy (see fig. 1 center). For laparoscopic hepatectomy, the surgeon must delineate a plane crossing the liver, along which the organ is then resected ([23]). A hepatectomy's quality depends on minimal resection of healthy tissue while removing all pathological tissue and a clean planar cut to avoid complications due bad vascularization of the edges of the remaining liver section. This supposes correct navigation of the instrument towards the resection plane, which can be a tricky task even for experienced surgeons.

The user's task was to guide the tip of the instrument along random trajectories starting from a peg tip and returning to it via both other peg tips. The task combined two conflicting precision and speed objectives. The main objective was to keep the tip of the instrument on the plane formed by the three pegs at all times and deviate as little as possible from it. The subject was free to choose the 2D trajectory thereby followed within the plane. The secondary objective was to execute the task in a minimum amount of time.

The forceps were fitted with infra-red reflective ball markers for tracking of the tool position and orientation via an optical tracking system (NDI Polaris™). The instrument was fitted with an electrical contact connected to an input pin on an Arduino UNO board allowing for detection of contact between the instrument tip and the peg tips. 3D positional data for the instrument tip, the computed associated normal deviation from the plane and

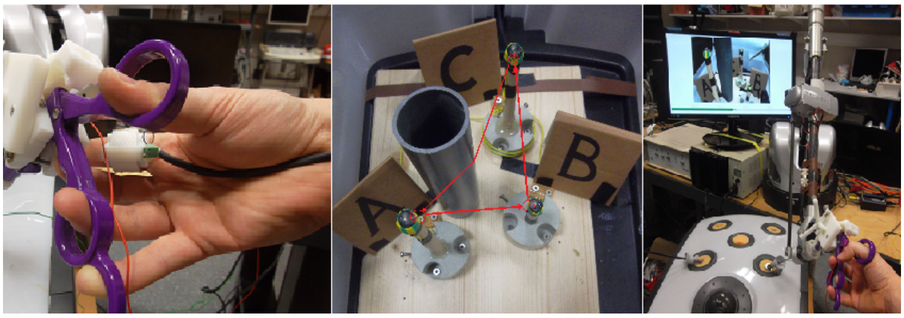

Fig. 1: Experimental setup, from left to right: Vibrotactile feedback via ERM motor attached to the subjects hand; View of the inside of the laparoscopic trainer and example of a trajectory; Combined kinesthetic and visual feedback using a 6DoF haptic interface.

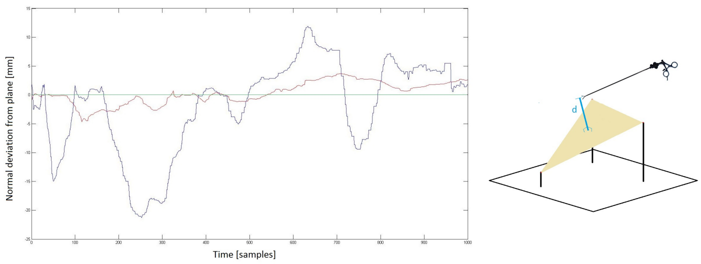

Fig. 2: **On the left:** Example of deviations measured for conditions L (blue) and KV (red) (see table 1 for details). **On the right:** The deviation is computed as the distance between the instrument tip and its normal projection in the target plane formed by the tips of the three pegs

associated timestamps were acquired via a PC with an average frequency of 58Hz (see fig. 2).

3 Methods

3.1 Initial exploratory experiment (R1)

In an initial experiment detailed in [15], 23 novice right-handed subjects performed 5 repeats of the task presented previously for the 11 different feedback conditions (i.e. a total of 55 trajectories per subject) listed in table 1.

Feedback informed the users of their normal deviation to the plane in various manners. We consider conditions as being "*without feedback*" when the user is presented with only the endoscopic image. Table 1 lists the feedback conditions relevant to our current analysis.

L	Laparoscopic surgery	Subjects manipulated a standard laparoscopic forceps tracked using optical markers inserted into the closed LaproTrain^{TM} through a 5mm trocar. The endoscope image was shown on a 24" screen placed at head height directly in front of the subjects. This basic set-up was kept for all conditions.
V	Laparoscopic surgery with visual feedback	Identical to L, except subjects were also provided visual feedback in the form of a bar-graph displayed beneath the endoscopic image.
T	Continuous vibrotactile feedback	Keeping the basic set-up from L, subjects were provided continuous proportional vibrotactile feedback as described above.
TV	Continuous vibrotactile + Visual feedback	Identical to T, with the addition of visual feedback as described above.
R	Inactive haptic interface	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 or friction. The objective was to assess to what extent this passive parallel co-manipulation set-up affected subject strategies and performance compared to L.
RV	Inactive haptic interface + Visual feedback	Identical set-up to R, however the subjects were provided visual feedback in the form of a bar-graph.
K (*)	Soft guidance virtual fixtures	Identical set-up to R, 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 below.
KV (*)	Soft guidance virtual fixtures + Visual feedback	Identical to K, with the addition of visual feedback as described previously.

Table 1: Feedback conditions for initial exploratory experiment. Conditions marked with (*) were only evaluated in our previous experiment as well as with the intern.

Visual feedback :

Visual feedback was provided in the form of a horizontal bargraph displayed on the screen(see fig. 1 right). The bar height changed to display the current deviation, which was also shown as a numerical value in [mm] at the center of the bargraph.

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) strapped to the inner side of the index finger holding the instrument (see fig. 1 on the left). This placement is interesting in the context of integration of vibrotactile feedback to the handle of serial co-manipulators for laparoscopic surgery. The distance to the target plane was encoded as a linearly increasing vibration

Statement :	1	2	3	4	5
1) I felt the task was difficult to perform in this condition					
2) I believe I performed well in this condition					
3) I understood the feedback *					
4) I felt the feedback helped me in accomplishing the task *					
5) I thought the feedback was intuitive *					
6) I was disturbed by the feedback *					
7) I felt the feedback was easy to use *					

Table 2: Questionnaire filled out by subjects after performing 6 repeats of the task in each condition. (*) marks statements only presented for conditions with feedback, i.e. L, V, TV and RV. Answer range from "Strongly disagree = 1" to "Strongly agree = 5"

intensity proportional to the magnitude of the deviation (range: 0g to 7g for deviations from 0mm to 30mm).

Evaluation of performances

Results were analysed both in terms of precision and time criteria. Relevant precision criteria encompassed both on-target precision (using a "*relative time on target*" (rToT) score, defined as the percentage of TCT during which the instrument tip was under 1mm normal deviation from the target plane) and amplitude of deviations. The evaluated time criterion was the TCT.

3.2 Second experiment (R2)

In the experiments discussed here, the task to be performed remained basically identical to that of the initial experiment. However, as the number of compared conditions was reduced, we were able to ask subjects to complete 6 trajectories per condition.

A new sample of 11 novice subjects (8 male, 3 female, all right-handed with no previous experience in laparoscopy or with our experiments) was asked to perform the task under provision of 4 different combinations of visual and vibrotactile feedback (L, V, T and TV detailed previously), as well as in conditions R and RV in order to assess whether improvements observed in these conditions during the initial experiments were due bias from learning effects.

For exploratory purposes, an intern with laparoscopic surgery training (male, right-handed, age 28) was asked to complete 10 trajectories respectively for conditions L, V, T, TV, R, RV, K and KV in order to gain insights into the generalizability of our results to a population of surgeons.

A questionnaire (see 2) presented as a five point Likert scale was filled out by subjects after performing the task in each feedback condition. The results are detailed and discussed in section 4.4.

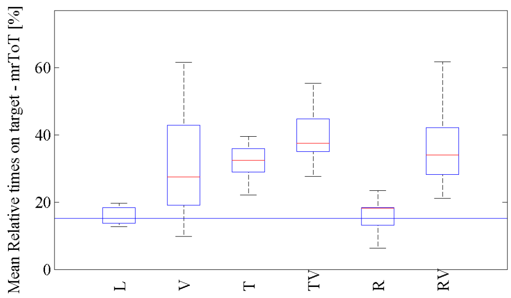

Fig. 3: Mean relative times on target (rToT) for second experiment. A horizontal blue line marks the median performance in the reference condition (L) for comparison purposes.

The order in which subjects performed the six conditions was fully randomized in order to minimize potential influence of short-term learning effects on our results.

4 Results and discussion

In the following, we present and discuss the results obtained in the second series of experiments, analysing them by themselves and subsequently in comparison with data from our previous experiments and exploratory data obtained from an intern. We compare mean performances for subjects in each feedback condition. Statistical significance of differences observed between condition pairs was performed using Wilcoxon signed-rank tests. Statistical significance of differences observed between data from experiment R2, experiment R1 and the interns performance was calculated for each condition using Mann-Whitney-Wilcoxon tests.

4.1 Precision criteria - Mean relative time on target (rToT)

As discussed previously, the first precision criterion we analysed was rToT, with higher value indicating better performance, on a scale ranging from 0% to 100%.

As expected, fig. 3 shows that conditions without feedback (R and L) lead to the worst performance in terms of rToT, with the median for condition L lying at 15.2%. Addition of visual, tactile or combined feedback improves performance with strong significance (see table 3), confirming our prior results. Performances in conditions V and T are not significantly different from one another, although we tend to observe much smaller spread of rToT values for condition T. Contrary to the results obtained in our initial experiment, condition TV leads better performances than condition T (strongly significant) and condition V (significant) respectively. Condition RV leads to an improvement over performance for condition R that is on par with that observed between

	V	**T**	**TV**	**R**	**RV**
L	12,3% (p<0,01)	17,2% (p<0,01)	22,2% (p<0,01)	2,9%	18,8% (p<0,01)
V	-	4,9%	10,0% (p<0,05)	-9,3% (p<0,05)	6,5%
T	-	-	5,0% (p<0,01)	-14,2% (p<0,01)	1,6%
TV	-	-	-	-19,3% (p<0,01)	-3,4%
R	-	-	-	-	15,9% (p<0,01)

Table 3: Differences in rToT between conditions

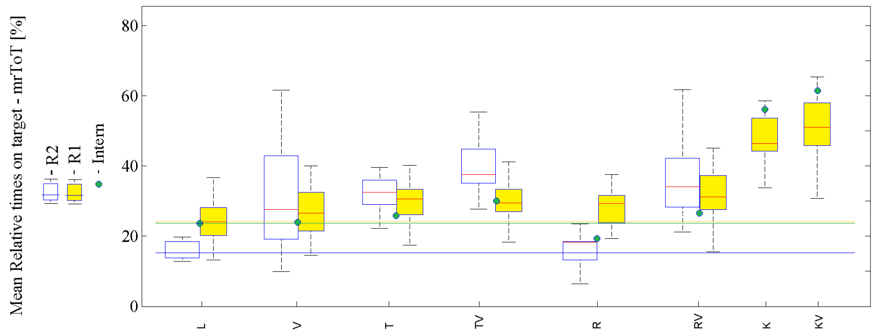

Fig. 4: Mean relative times on target (rToT) compared between first (yellow box-plot) and second (white box-plot) experiments as well as data for one intern (green dots)

conditions L and V, with no significant difference observed between performances in RV and those in V, T and TV respectively. No significant differences are observed between conditions L and R, and V and RV respectively, leading us to conclude that significant differences observed between these conditions in R1 were in fact introduced by bias due to learning effects.

Table 3 summarizes the magnitudes of observed differences in rToT between conditions along with calculated p-values for statistical significance whenever relevant. All difference values are calculated as the median of rToT for the column condition minus the median of rToT for the row condition, i.e. a positive value in row L, column TV indicates a higher (and thus better) rToT for condition TV when compared to condition L.

Table 4 summarizes the magnitudes of observed differences in rToT within conditions, between the first round (R1) of experiments, second round (R2) of experiments, and performance data from one intern, along with calculated p-values for statistical significance whenever relevant. Difference values are calculated as :

$$(X - Y) = median(rToT_X) - median(rToT_Y) \tag{1}$$

where X and Y are to be replaced by R2, R1 or Intern depending on the column considered.

Overall, we can observe the same patterns of improvements between conditions in the data from our initial experiment (R1), that from our second experiment (R2) and the exploratory data obtained from the intern. The only

Conditions	R2 - R1	Intern - R1	Intern - R2
L	-8,8% (p<0,01)	-1,8%	6,9%
V	1,0%	-4,1%	-5,1%
T	1,9%	-6,2%	-8,1%
TV	7,9% (p<0,01)	1,4%	-9,3%
R	-11,1% (p<0,01)	-11,2%	0,1%
RV	2,7%	-6,4%	-9,1%
K	-	6,2%	-
KV	-	6,6%	-

Table 4: Differences in rToT between first and second round of experiments as well as data from one intern

significant differences between experiments R1 and R2 can be observed for conditions L and R (strongly significant degradation of performance between R1 and R2) and for condition TV (strongly significant improvement between R1 and R2). We believe that bias from learning effects and fatigue in R1 could explain this observation for conditions R and TV.

In terms of precision, data obtained from the intern does not significantly differ from that of novices. However, considering the fact that the intern completed the task with significantly lower TCT (see section 4.3), we conclude that the provided feedback positively impacted task performance in terms of the speed-accuracy trade-off. It is interesting to note that visual feedback alone (V) seems to yield no improvement in rToT, whereas conditions with tactile feedback (T, TV) yield marginal improvements over the reference condition (L). Also, the significant improvement observed between condition L and kinaesthetic feedback conditions (K and KV) appears to be more pronounced for the intern when compared to novices. This could hint at a more optimal use of the feedback and guidance due to familiarity with laparoscopic tasks, although this conclusion remains quite tentative since we only have data from one intern.

4.2 Precision criteria - Mean deviation amplitudes (DA)

Another important measure of precision with clinical relevance is the maximum error in any given condition. Mean deviation amplitudes (i.e. the maximum positive deviation from the plane minus the maximum negative deviation from the plane) shown in figure 5 confirm our previous results.

Similarly to table 3, table 5 summarizes the magnitudes of observed differences in DA between conditions along with calculated p-values for statistical significance whenever relevant.

We once again note that providing any form of feedback on the deviation yields improved performances (i.e. lower deviation amplitudes), however differences are only strongly significant between conditions TV and L, and conditions RV and R respectively. In line with previous results, we once again observe that the combination of visual and tactile feedback significantly improves

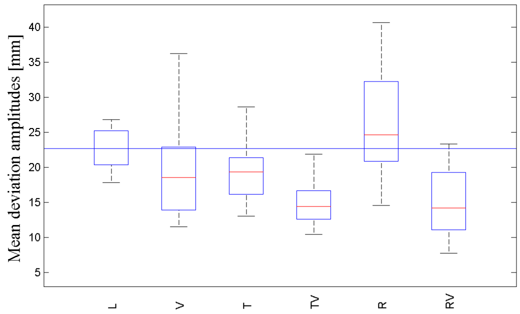

Fig. 5: Mean deviation amplitudes (DA) for second experiment

	V	T	TV	R	RV
L	-4,2mm	-3,3mm	-8,3mm ($p<0,01$)	1,9mm	-8,5mm ($p<0,01$)
V	-	0,8mm	-4,1mm ($p<0,05$)	6,1mm ($p<0,05$)	-4,4mm ($p<0,05$)
T	-	-	-4,9mm $p<0,01$)	5,3mm $p<0,01$)	-5,2mm $p<0,01$)
TV	-	-	-	10,2mm $p<0,01$)	-0,3mm
R	-	-	-	-	-10,4mm $p<0,01$)

Table 5: Differences in DA between conditions

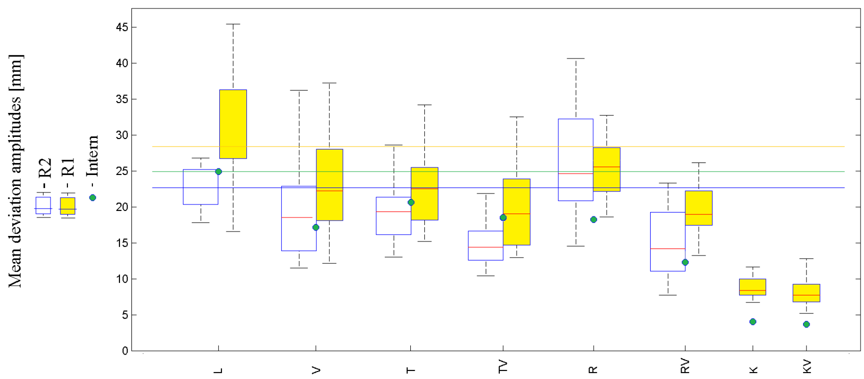

Fig. 6: Mean deviation amplitudes (DA) compared between first and second experiments as well as data for one intern

performance over conditions V and T with significance ($p<0.05$) and strong significance ($p<0.01$) respectively. No significant differences are observed between conditions L and R, leading us to conclude that significant differences observed between these conditions in R1 were in fact introduced by bias due to learning effects. On the other hand, DAs for RV are significantly larger than for V, which, contrary to our previous results, could indicate a disturbing effect of the inactive haptic interface.

Similarly to table 4, table 6 summarizes the magnitudes of observed differences in DA within conditions, between the first round (R1) of experiments,

Conditions	R2 - R1	Intern - R1	Intern - R2
L	-5,7mm	-3,4mm	2,3mm
V	-3,7mm	-4,9mm	-1,2mm
T	-3,2mm	-1,6mm	1,5mm
TV	-4,6mm	0,5mm	4,1mm
R	-1,0mm	-7,3mm	-6,3mm
RV	-4,8mm	-6,5mm	-1,7mm
K	-	-4,3mm	-
KV	-	-4,0mm	-

Table 6: Differences in DA between first and second round of experiments as well as data from one intern

second round (R2) of experiments, and performance data from one intern, along with calculated p-values for statistical significance whenever relevant.

In terms of DAs, no significant differences in performance are observed between novice subjects from our initial experiment (R1) and second experiment (R2) and the intern. Overall, figure 6 shows very similar patterns of improvements between conditions for all three groups of subjects, with a general tendency towards lower deviation amplitudes for novice subjects in our second experiment (R2) and the interns performance more or less identical to that of the novices (which must once again be considered along with his drastically reduced TCTs), except in the kinaesthetic feedback conditions (K and KV), where the intern attains excellent performances (DA<5mm), confirming our previous remarks on rToT. We believe the overall better performance by subjects from R2 when compared to R1 reflects effects of subject fatigue due to the particularly long duration of the protocol for R1 (above 1h on average, against 35 minutes on average for R2).

4.3 Speed criterion - Mean time to complete task (TCT)

When considering speed criteria, we observe results similar to those from our previous experiments in figure 7. Providing feedback of any kind (conditions V, T, TV and RV) tends to slow down execution of the task when compared with the speed of task execution in reference conditions (L and R respectively). These increases in TCT are all strongly statistically significant. Similarly to results from R1 and the literature, we note that condition T seems to induce a more limited increase in TCT than conditions with visual feedback (V and TV), which could reflect lower cognitive load in this condition, although the difference is not statistically significant. The improvements between L and R, and V and RV observed in R1 are not reflected in these results, in fact R tends to require longer TCTs than L (although not significantly). This confirms our conclusion that improvements observed in R1 are probably due to bias from learning effects.

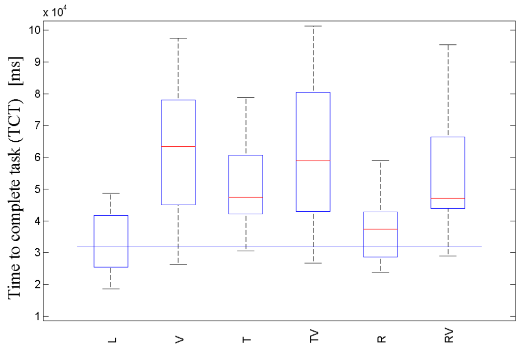

Fig. 7: Mean times to complete task (TCT) for second experiment

	V	T	TV	R	RV
L	31,6s (p<0,01)	15,7s (p<0,01)	27,1s (p<0,01)	5,6s	15,2s (p<0,01)
V	-	-15,9s	-4,5s	-26,0s (p<0,01)	-16,4s
T	-	-	11,4s	-10,1s	-0,5s
TV	-	-	-	-21,5s (p<0,01)	-11,9s
R	-	-	-	-	9,6s (p<0,01)

Table 7: Differences in TCT between conditions

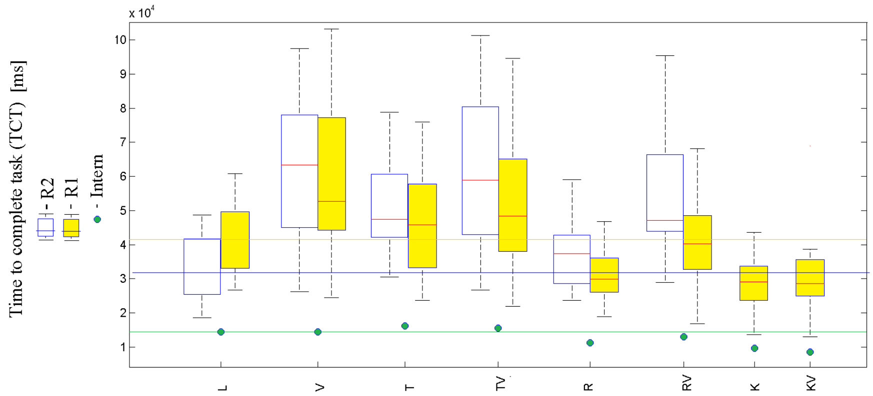

Fig. 8: Mean times to complete task (TCT) compared between first and second experiments as well as data for one intern

Similarly to table 3, table 7 summarizes the magnitudes of observed differences in TCT between conditions along with calculated p-values for statistical significance whenever relevant.

Similarly to table 4, table 8 summarizes the magnitudes of observed differences in TCT within conditions, between the first round (R1) of experiments, second round (R2) of experiments, and performance data from one intern, along with calculated p-values for statistical significance whenever relevant.

Conditions	R2 - R1	Intern - R1	Intern - R2
L	-9,7s	-28,0s	-18,3s
V	10,7s	-39,0s	-49,8s
T	1,7s	-30,5s	-32,2s
TV	10,6s	-34,0s	-44,3s
R	7,6s	-19,3s	-26,9s
RV	6,8s	-28,0s	-34,8s
K	-	-20,1s	-
KV	-	-20,6s	-

Table 8: Differences in TCT between first and second round of experiments as well as data from one intern

Once again, we observe similar trends in improvements between conditions for all three subject groups. There is little difference between novice subjects from R1 and R2, but the intern is clearly set apart with TCTs almost halved for every condition when compared to novice subjects (the observed differences do not reach statistical significance but come very close, with calculated p-values for differences between TCTs for the intern, R1 and R2 respectively between 0.11 and 0.16). Interestingly enough, we still see a slight increase in TCT between conditions without feedback (L and R) and conditions with feedback (V, T, TV and RV), but this increase is much less pronounced for the intern when compared to novice subjects. This is encouraging as it could indicate that familiarity with laparoscopic tasks allows for more efficient use of feedback, suppressing the disadvantageous effect of increased TCTs when feedback is provided. A study on a larger population of surgeons and interns is however required to confirm this hypothesis.

Interestingly, virtual fixtures significantly reduce TCT for both novices subjects from experiment R1 and an intern, further confirming possible generalizability of our results.

4.4 Qualitative analysis of subject perception

As previously described, a five point Likert scale was used to assess the subjects perception of various impacts of the provided forms of feedback (see table 2). In the following, we discuss the results question by question.

Impact on perceived difficulty and self-assessed performance for the task

The first statement in our questionnaire aimed to assess potential impacts of adding feedback on user perceived task difficulty. Statement (2) aimed to assess the impact on users self-assessed performance. From the novice subject's perspective, it appears that feedback does not impact perceived difficulty of the task despite subjects performing better with it.

Combining vibrotactile with visual feedback seems to significantly correlate with a drop in self-assessed performance (mean score drop by 0,1 (p¡0,05)), whereas performing the task in condition R correlates with an increase in self-assessed performance (mean score increase by 0,27 (p¡0,01)). These results may indicate a negative effect from a perceived excess of information in condition TV, and a reassuring effect obtained when co-manipulating the instrument with a passive haptic interface.

User understanding of the feedback

Statement (3) in our questionnaire aimed to assess a given subjects understanding of the feedback obtained during the task. Condition V appeared significantly clearer than condition T (mean score difference of 0,18 (p¡0,05)), which in turn outperforms condition VT (though not significantly).

Assisting and disturbing effects of feedback

Statement (4) assessed the perceived user comfort for using each form of feedback and statement (5) assessed the level of intuitiveness of the encoding for the current deviation from the target. Condition VT was evaluated as significantly easier to use than condition T (mean score difference of 0,1 (p¡0,05)), but harder to use than condition V (mean score difference of 0,27 (p¡0,01)). This first result could be due to the fact that the visual feedback provided additional directional information about the deviation, easing the task, and the second result probably reflects the complexity of dealing with tactile and visual cues simultaneously.

The sixth statement in our questionnaire aimed to assess the perceived quality of assistance from each form of feedback, and the last statement in our questionnaire aimed to assess potential disturbances in task execution resulting from providing feedback. Visual feedback conditions (V and TV) were deemed slightly more helpful but less intuitive than tactile feedback alone, however no statistically significant difference was observed.

5 Conclusion

In this paper, we confirm previous results indicating that in a 1D guidance task, visual and cutaneous vibrotactile feedback as well as their combination lead to improved performances in terms of precision at the cost of increased TCTs. Our shortened and fully randomized experimental protocol minimized contributions from learning effects in the observed differences.

We also compared data for novice subjects with an interns performances, showing no significant differences in terms of precision but a significantly lower TCT at equal precision. Overall, the patterns of improvement over the reference condition obtained in novice subjects for conditions V, T, TV, K and KV can be found again in the interns performance, leading us to believe in a good chance of our results being generalizable to a population of surgeons with similar results. Interestingly, the intern performed better in conditions T and TV than in condition V, which may indicate a lower cognitive load when using feedback presented though tactile cues instead of visual cues. Similarly to our previous experiments, we note that visual feedback still seems beneficial, particularly in avoiding larger deviation amplitudes. Finally, the intern's TCTs seemed much less affected by the provision of feedback, which stands out as a particularly interesting feature when considering clinical applications of such feedback.

Analysis of novice subject's perception of the usability and impact of the provided feedback on their performance revealed that presence or lack of feedback does not seem to have any significant effect on the perceived difficulty of the task. The self-assessed performance of the users is however significantly improved in condition R over condition L, which could indicate higher confidence during co-manipulation of the instrument, and in condition V over condition TV, indicating a potentially disturbing effect from the excess of information provided in condition TV. Overall, the subjects seemed to understand the feedback well in all conditions, with significantly better understanding reported for conditions V and RV when compared to condition T. We believe this to be linked to the fact that our visual feedback through the bar-graph provided additional directional information whereas the vibrotactile feedback only provided information on the magnitude of the deviation from the target and was harder to interpret. When comparing perceived assistance from the various forms of feedback, all conditions seem to do equally well, with the only significant improvement being between conditions RV and V, which we once again speculate is due to a higher user confidence when co-manipulating the surgical tool. All forms of feedback are perceived as equally easy to use, with the exception of condition TV, which scores significantly lower than T, hinting at complexity arising from an excess of information. This is reflected in the perceived intuitiveness of the provided feedback, where TV again scores significantly lower than V. When asked about potential disturbances in task execution arising from the feedback, subjects tend to be undisturbed, with no significant differences between forms of feedback.

6 Future work

These promising initial results for the use of cutaneous feedback are leading us to consider extending the evaluation of such forms of feedback to more complex guidance tasks (i.e. 2D and 3D trajectories), while performing a comparative evaluation of various forms of tactile feedback in order to improve performance and intuitiveness of the feedback. Furthermore, there was little to no contact between the instrument and structures placed within the trainer in this study. In order to assess the viability of such forms of feedback for clinical applications, it will be imperative to evaluate their use in tasks involving physical interaction within the trainer, e.g. dissection or suturing tasks. Finally, we aim to test generalizability of our results to a population of surgeons.

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