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Vibrotactile guidance for trajectory following in Computer Aided Surgery

Jeremy Bluteau*, Marie-Dominique Dubois†, Sabine Coquillart†, Edouard Gentaz* and Yohan Payan*

Abstract—Most conventional computer-aided navigation systems assist the surgeon visually by tracking the position of an ancillary and by superposing this position into the 3D preoperative imaging exam. This paper aims at adding to such navigation systems a device that will guide the surgeon towards the target, following a complex preplanned ancillary trajectory. We propose to use tactile stimuli for such guidance, with the design of a vibrating belt. An experiment using a virtual surgery simulator in the case of skull base surgery is conducted with 9 naive subjects, assessing the vibrotactile guidance effectiveness for complex trajectories. Comparisons between a visual guidance and a visual+tactile guidance are encouraging, supporting the relevance of such tactile guidance paradigm.

I. INTRODUCTION

Computer-Aided Surgery (CAS) has become an accepted way of assisting surgeons during complex surgical interventions. These navigation systems provide an on-line tracking of surgical tools (or “ancillaries”, often tracked by stereo cameras and markers) which positions are superimposed into previously acquired medical investigation such as computer tomography (CT), magnetic resonance imaging (MRI) or ultrasound images (US). The use of imaging technologies leads to possible 3D reconstructions and preoperative planning, depending on the medical intervention.

Most conventional CAS systems inform the surgeon about the distance of the ancillary relative to anatomical structures as well as preplanned data (safety areas, tumor, predefined trajectory,...). This information is usually provided through visualization devices (a screen) located beside the operative field, two or three meters away from the surgeon. Quite recent researches tried to improve this visual feedbacks by (1) simplifying the amount of guidance information or (2) using another perception channel. In the first class of improvements, some punction applications like kidney biopsies or computer assisted systems for pedicle screw insertion display visual guidance by aligning crosses [7], [5]. These applications are restricted to straight trajectories. The second class of improvements propose to use another sensory channel for such guidance. Auditory channels have been extensively used, mainly because of their temporal efficiency [8]. However, their omnipresence as physiological variables alarms dissuades their use for on-line continuous guidance. Recently, researchers have tried to use a still non-overloaded sensory modality namely the tactile channel. Due to the large amount of sensitive receptors on the tongue, researchers have shown that guidance of surgical gestures such as biopsies or target hit can be achieved by electro-tactile stimulation of the tongue thanks to a Tongue Display Unit [11], [10], [9]. Even if efficiency have been demonstrated, efforts on ergonomics, discomforts and pattern of information coding are still needed [10]. Other researches focused on the stimulation of the skin by vibrations. Vibrators can actually be placed on the dorsal face of the hand [2], or mounted on a belt, worn on the abdomen, torso or forearm [8]. Brell et al. [2] proposed a four vibrators tactile glove tracked by stereo cameras which indicates the correct position of the surgical tool. Results showed a less than 5 mm error to the target but problems of overshooting and oscillations during the trajectory following task. Ng et al. [8] demonstrated that tactile modality leads to higher reaction time compare to auditory stimulation but far lower reaction time compare to visual modality. Our project is more generally dedicated to a better characterization of the influence of these vibrotactile modalities onto the human performance during complex, online, and non straight trajectories following tasks. Since it is a surgical gesture that needs quite complex trajectories path to access the target, skull base surgery was chosen for our study.

II. MATERIAL AND METHODS

A. Vibrotactile feedbacks

The proposed solution is composed by vibrators, mounted on a belt worn by the participants around the abdomen. The control of vibration motors is provided by an USB controller card and relays (www.phidgets.com). Two design configurations were proposed, in order to experiment two different guidance paradigms. The first design (Belt1) is composed by 6 tiny vibrators (ø 6 mm) which can run with two vibration levels (≈5000 rpm and ≈2000 rpm). The activation of one of the 6 relays stands for the motor selection, the two last relays stand for the selection of the level of vibration (realized by adding resistors). The second design (Belt2) is composed by 8 vibrators with a single level of vibration (≈5000 rpm). In that case, two mounting belts are used, each composed by four motors. The vibration motors of belts 1 and 2 are manually arranged around the abdomen of the subjects to fit their anatomy, depending on the guidance paradigm used (see below). For development purposes, not encapsulated motors are used and firmly mounted on the belt with the secure
from the lower and the higher mounting belts is possible

vibrators of each mounting belt is sequential but activation

the tool (distal position). The activation of one of the four

surgeon), while the lower belt stands for the extremity of

proximal position of the tool (close to the hand of the

Two sets of four motors are located on the cardinal points

cf. is based on the 8 vibrators of Belt2 (fig. 1, bottom).

perfectly aligned with the planned trajectory, no vibration is

but in parallel with the frontal vibrators. When the tool is

orientation of the tool. They are also sequentially activated

of the two mounting belts. The higher belt stands for the

skull base surgery, the surgeon has to drill into the patient

allow real differences in the touch of different structures

preoperative CT exam. It is important to note here that two

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surgical tools are restored to the user by a PHANToM Omni

visualization. Haptic force feedbacks were required for the

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sections as in real computer-navigated surgery and was also

used for the simulation rendering. This second role can

patient’s head based on iso surfaces generation was com-

herent in this type of simulators [4]. A general overview

with different trajectories, despite the lack of realism inher-

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solution allowed us to repeat the experiment many times,

with different trajectories, despite the lack of realism in-

regarding the structures to reproduce. Therefore, we used real anatomical data from

a patient to build a simulator of the surgical gesture. This

reproduction of the simulation, otherwise the participants would

realism of the simulation, otherwise the participants would

be decomposed in two main parts: haptic rendering and visualiza-tion. Haptic force feedbacks were required for the

realism of the simulation, otherwise the participants would

not have been able to feel any contact with the virtual model,

and therefore would not have been able to reproduce the

surgery. Forces and contacts between virtual structures and

surgical tools are restored to the user by a PHANToM Omni
device (www.sensable.com). Stiffness values were linearly

derived between 0 and 2 N from the voxels intensity of the

preoperative CT exam. It is important to note here that two

voxels with similar intensities rendered the same stiffness

haptically. Even if these values were approximated, they

allow real differences in the touch of different structures

such as bones, soft tissues, cavities, and vessels. During a real

skull base surgery, the surgeon has to drill into the patient

head bones. Simulating such interaction is still a complex

issue [4] and has been solved by implementing the method

proposed by [3], [6]. We strongly encourage the reader to

refer to [1, chap. 8] for implementation details.

B. Guidance paradigms

Two guidance paradigms associated to the two belts use
(Belt1 or 2) were proposed. Our objective was to evaluate
whether participants were more efficiently guided by one
belt or the other one, suggesting different mental spatial

representations of the task.

1) Guidance paradigm 1: This guidance paradigm is
composed by 4 frontal vibrators located on the anterior side
of the Belt1, indicating side and horizontal changes (yaw)
in the orientation of the tool. Each vibrator is activated
sequentially, depending on the angles figured in fig. 1 (top).

The level of vibration is given by the difference between
the current tool orientation and the planned trajectory. If the
difference is higher than half of the triggering threshold then
the vibration level is high, else it is set to low. Two vibrators
are placed at the back of the belt, standing for the pitch
orientation of the tool. They are also sequentially activated
but in parallel with the frontal vibrators. When the tool is
perfectly aligned with the planned trajectory, no vibration is
given to the user.

2) Guidance paradigm 2: This second guidance paradigm
is based on the 8 vibrators of Belt2 (cf. figure 1, bottom).
Two sets of four motors are located on the cardinal points
of the two mounting belts. The higher belt stands for the
proximal position of the tool (close to the hand of the
surgeon), while the lower belt stands for the extremity of
the tool (distal position). The activation of one of the four
vibrators of each mounting belt is sequential but activation
from the lower and the higher mounting belts is possible
simultaneously. Activations are based on difference of the
tool position and orientation to the theoretical trajectory,
starting with a distance of 0.02 mm. The same yaw and

pitch information are then possible.

3) Coding schemes: In addition, two schemes for di-
rection coding are proposed, for both belts: demonstration
coding, where the belt indicates the orientation to provide to
the tool to be aligned with the theoretical planned trajectory;
or correction coding, where the belt indicates the current
alignment errors. These coding schemes are related in the
literature as “direction coding” and “avoiding coding” [9].

C. Surgery simulator

To reproduce a situation similar to the actual skull base
surgery and in order to quantitatively evaluate the tactile
guidance, we decided to develop a virtual surgery simulator.
Indeed, experiments on real anatomical pieces introduce a
large amount of logistical and ethical problems (access to CT
and MRI for the preoperative images, cadaver experiments).
On the other hand, the uniqueness of those configurations
that can not be validated by several experts or do not allow statistical analysis of large scale was not suitable for
our purpose. Achieving a specific head phantom, dedicated
to this experience revealed to be technically too complex
and anatomically too simplistic regarding the structures to
reproduce. Therefore, we used real anatomical data from
a patient to build a simulator of the surgical gesture. This
solution allowed us to repeat the experiment many times,
with different trajectories, despite the lack of realism inher-
ent in this type of simulators [4]. A general overview
of the simulator is pictured in fig. 2. After registration of
the preoperative data (CT and MRI), a 3D model of the
patient’s head based on iso surfaces generation was com-
puted. This data set was used for the display of anatomical
sections as in real computer-navigated surgery and was also
used for the simulation rendering. This second role can
be decomposed in two main parts: haptic rendering and
visualization. Haptic force feedbacks were required for the
realism of the simulation, otherwise the participants would
not have been able to feel any contact with the virtual model,
and therefore would not have been able to reproduce the
surgery. Forces and contacts between virtual structures and
surgical tools are restored to the user by a PHANToM Omni
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head bones. Simulating such interaction is still a complex
issue [4] and has been solved by implementing the method
proposed by [3], [6]. We strongly encourage the reader to
refer to [1, chap. 8] for implementation details.
A. Experiment 1

After the training phase, subjects had to choose a coding scheme (either demonstration or correction) for each belt type. None of the participants choose the Belt1 with a correction coding or the Belt2 with a demonstration coding. We had therefore only three conditions to test during the performance assessment: Belt1-D, Belt2-C and Visual Only. For each measured criterion (raw data are summed up in the table I), an ANalysis Of VAriance (ANOVA) in repeated measurements (3 conditions x 6 trials) was computed. The influence of the order was not significant (as expected by the experimental protocol design) except for the mean error. Further analysis of this last criterion was cancelled. For maximum error criterion, a significant effect ($F(2,16) = 11.0; p < .01$) was found between conditions. Newman-Keuls post-hocs tests detailed this effect by showing a significant difference between conditions Belt1-D and Belt2-C ($p < .01$); and a significant difference between conditions Belt1-D and Visual Only ($p < .01$). No significant difference was found between Belt2-C and Visual Only ($p > .25$). Concerning duration, the ANOVA revealed no significant effect between conditions ($p > .25$). Finally,
dealing with mean velocity criterion, a significant effect was found \( F(2, 16) = 5.54; p < .05 \) between conditions. Post hoc tests (Newmans-Keuls) revealed significant differences between Belt1-D and Visual Only.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Belt1-D</th>
<th>Belt2-C</th>
<th>Visual only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (s)</td>
<td>23.07 ± 4.37</td>
<td>23.07 ± 4.37</td>
<td>17.19 ± 1.82</td>
</tr>
<tr>
<td>Mean velocity (mm/s)</td>
<td>10.83 ± 2.79</td>
<td>10.83 ± 2.79</td>
<td>10.65 ± 1.23</td>
</tr>
<tr>
<td>Mean error (mm)</td>
<td>3.01 ± 0.16</td>
<td>3.01 ± 0.16</td>
<td>3.01 ± 0.16</td>
</tr>
<tr>
<td>Maximum distance (mm)</td>
<td>16.51 ± 1.69</td>
<td>16.51 ± 1.69</td>
<td>16.51 ± 1.69</td>
</tr>
</tbody>
</table>

**B. Experiment 2**

Similar ANOVAs in repeated measurements (2 conditions x 6 trials) were computed for each criterion (raw data are given in table II). The order effect was not significant (as expected) \( (p > .25) \). All computed criterions, except duration \( (p > .25) \), revealed significant differences between tactile conditions (Belt1-D and Belt2-C groups with respectively 2 and 7 subjects) and Visual Only condition (mean velocity: \( F(1, 8) = 7.10; p < .05 \); mean error: \( F(1, 8) = 6.72; p < .05 \); maximum distance: \( F(1, 8) = 7.87; p < .05 \) and time looking navigation screen: \( F(1, 3) = 11.64; p < .05 \).

**IV. DISCUSSION, CONCLUSIONS AND FUTURE WORKS**

The present study examined whether vibrotactile guidance can bring beneficial clues to realize a complex task of trajectory following, as encountered in skull base surgery. The results from experiment 1 showed a strong difference between our two guidance paradigms. The Belt1 paradigm revealed to be significantly different from Belt2 and visual control conditions, with performances that tend to be lowered, suggesting a mismatch to the underlying mental representation. Belt2 paradigm showed equivalent performances as control condition. The lack of participants choosing Belt1-C or Belt2-D suggests a cognitive inadequacy between coding and guidance paradigm. The results of the second experiment on a simulated skull base surgery showed a significant reduction of spatial errors (mean and maximum errors), a decrease of mean velocity, a significant reduction of the need for visual feedbacks (percentage of time looking at the navigation screen) and no significant differences in the duration, for the tactile guidance condition as compared to the control condition. It seems therefore that the proposed tactile guidance, even after a short familiarization period, can efficiently provide the localization information that are usually brought by the navigation systems, as emphasized by the reduction of the time passed to look at visual localization information. The interest for skull base surgery, and more generally speaking for complex on-line trajectories following, can be important with the objective to reduce the distance errors and to let the surgeon focus his/her attention to the operative field. However, this research only focused on a comparison between tactile guidance and the usual way of performing skull base surgery. A confrontation to other visual guidance \([7]\) might precise the efficiency of such tactile guidance. We also need to investigate the target population (i.e. surgeons) to see if these promising results are confirmed. For informed, preliminary results with one surgeon tend to confirm the positive effect of our tactile guidance. Other in situ experiments should also be conducted but the implementation implies further developments as concerns the tool tracking.

In conclusion, a surgery simulator was used to assess if a vibrotactile guidance could be implemented for complex trajectories following task. Two guidance paradigms were proposed based on two vibrotactile belts, showing significant differences in performances for naïve participants. Results seem to be very encouraging for an application in skull base surgery but further experiments need to be conducted on experts to be more specific about the effects of this tactile guidance in real operating conditions.

**REFERENCES**


