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Preliminary evaluation of a multi modal simulator for freehand ventriculostomy

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INTRODUCTION

Ventriculostomy is one of the most frequent procedures in neurosurgery [1]. It involves puncturing the ventricle to drain cerebrospinal fluid. In Freehand Ventriculostomy (FV), neurosurgeons first palpate external anatomical landmarks before blindly inserting the catheter. Their trajectory is guided by their mental projection of the needle path and internal anatomy from pre-op MRI scans. During the insertion, surgeons heavily rely on haptic feedback to control their gestures. This technique is still preferred over existing image-assisted procedures due to the extra effort the latter requires [2]. Despite its prevalence, the accuracy of FV is a controversial topic. Insufficient training has been linked to additional risks for the patients [2] and surveys have demonstrated that junior residents needed more passes (2.4) than senior ones (1.4) to puncture the ventricle, with a success rate between 72% and 84% [3].

To address the limitations of current training and due to the limitations of purely virtual simulators [4], haptic training simulators have been considered. They are broadly classified into three categories [5]: Physical Simulators (PS), Virtual Reality Simulators (VRS), and Mixed Reality Simulators (MRS). PS and MRS permit palpation; however, they suffer from low reusability and low diversity. VRS combine visual and Active Haptic Feedback (AHF) but are costly and lack physical anatomical landmarks. According to the expert neurosurgeons taking part in this preliminary evaluation, these limitations prevent the adoption of such technologies in the training curriculum.

Therefore, a multi-modal training simulator for FV was introduced in 2023 [6], providing visual and force feedback associated with tangible anatomical landmarks (as required in clinical practice) while improving the reusability and diversity of PS and MRS. This paper introduces a preliminary subjective evaluation of this simulator by 17 international expert neurosurgeons.

MATERIALS AND METHODS

The simulator conveys three types of information. Users evaluate the geometry of internal anatomy on displayed MRI slices (see (I) in Fig. 1-a). As an educational feature, the position of the needle tip can be displayed on the MRIs. During simulation, the user interacts with virtual anatomy constructed through MRI segmentation (see (II) in Fig. 1-a), using a commercial haptic interface (see (III) in Fig. 1-b). It provides force feedback and connects the

tangible parts of the simulator to the virtual anatomy and MRIs. The 3D-printed skull (see (IV) in Fig. 1-b), designed according to MRI scans, displays relevant anatomical landmarks, the nasion, the coronal suture, and the top of the ear. It is essential for the realism of the simulation that all these elements are well collocated to provide consistent visual, haptic, and proprioceptive information. During the simulated insertion, tip forces and friction forces are rendered to the user. Tip forces due to the deformation and rupture of the meninges (1) and the cutting of the parenchyma (2) are illustrated in Fig. 1-c. The puncture (3) is marked by a sudden drop in forces.

The simulator was tested by 17 expert neurosurgeons at the 2024 Consensus Conference and 6th Refresher Course of the European Society for Pediatric Neurosurgery (ESPN). Participants, who gave their informed consent had performed more than 20 FV and still practiced regularly (monthly or weekly). Out of the 17 experts, 12 (70.6%) had never practiced on simulators during training, 3 (17.6%) had trained on cadavers or mannequins, and only 2 (11.8%) had prior experience with simulators. They were asked to perform the FV on our multi-modal simulator. To do so, surgeons could browse the MRI scans, palpate anatomical landmarks, and measure reference points both on scans and on the printed skull.

After completing their FV trial, experts were asked to fill out a survey consisting of seven questions (summarized in Table I) that were answered on a 5-level Likert Scale. The survey focused on the novelty of this simulator in the context of FV training, i.e. the combination of AHF and tangible anatomy. First, three questions concerned the relevance of the simulator's design (see *About this simulator* in Table I) regarding the potential benefits in the training and evaluation of FV and the appropriateness of tangible anatomical landmarks. Then four questions concerned the realism of force feedback (see *Do you feel that the force feedback is realistic* in Table I).

RESULTS

It is clear from the answers (summarized in Table I) that expert surgeons believe our multi-modal simulator could have a positive impact on training. According to 82.4% of the experts this simulator could be beneficial to the current training curriculum and 76.5% agree that it could allow for a precise evaluation of students. Although experts

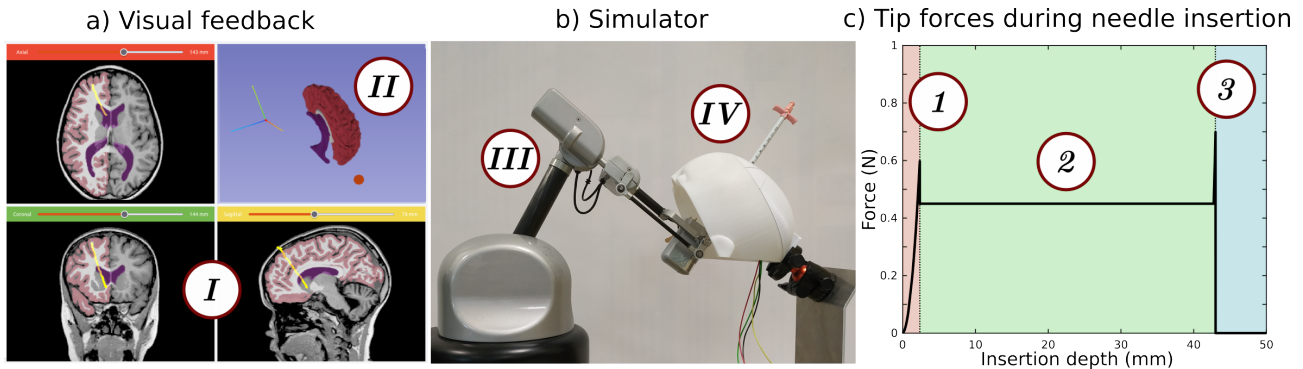


Fig. 1: Overview of the multi-modal simulator.

	Agree	Slightly agree	Without opinion	Slightly disagree	Disagree
About this simulator					
Its integration into the training curriculum can be of real benefit in learning how to perform the freehand ventriculostomy	14 (82.4%)	3 (17.6%)	0 (0%)	0 (0%)	0 (0%)
Its use could allow for a precise evaluation of the student during freehand ventriculostomy training	13 (76.5%)	3 (17.6%)	1 (5.9%)	0 (0%)	0 (0%)
The skull and anatomical landmarks are sufficient in their current form	6 (35.3%)	7 (41.2%)	1 (5.9%)	3 (17.6%)	0 (0%)
Do you feel that the force feedback is realistic					
As a whole	12 (70.6%)	2 (11.8%)	1 (5.9%)	1 (5.9%)	1 (5.9%)
Across the meninges	7 (41.2%)	6 (35.3%)	1 (5.9%)	2 (11.8%)	1 (5.9%)
Across the parenchyma	11 (64.7%)	4 (23.5%)	0 (0%)	1 (5.9%)	1 (5.9%)
When puncturing the ventricle	12 (70.6%)	3 (17.6%)	0 (0%)	1 (5.9%)	1 (5.9%)

TABLE I: Results of the subjective evaluation of the multi-modal simulator.

concluded on the potential benefits of the simulator, opinions were more divided regarding anatomical landmarks according to the results. In complementary comments and during interviews, some experts suggested that having the complete nose and ears could be useful.

Force feedback was overall well received. 70.6% of expert neurosurgeons agreed that insertion forces were rendered realistically throughout the insertion. Although the cutting of the parenchyma and the puncture of the ventricle were found realistic (64.7% and 70.6% agreed respectively), the rupture of the meninges was less convincing to the experts. Indeed, 41.2% agreed and 35.3% slightly agreed on the realism of the force feedback for the meninges. Only very few experts rated the realism of the simulator negatively. It is worth noting that only one expert completely disagreed on the realism of the force feedback. Still, this expert slightly agreed on the positive impact of the simulator in the training curriculum.

CONCLUSIONS AND DISCUSSION

In this paper, a first subjective evaluation of the multi-modal simulator for FV training was introduced. This preliminary evaluation was conducted by 17 international expert neurosurgeons who still practice FV on a regular basis. It aimed to validate the overall design of the simulator and relied on surveys regarding the anticipated benefits of integrating simulation into training. Although encouraging, these results are not yet definitive and will need to be generalized with more participants, including

novice surgeons as well. Still, these preliminary tests confirmed the value of designing a multi-modal simulator for FV training. Future work will be organized in two parts. First, several improvements will be brought to the simulator regarding anatomical landmarks and force feedback. One of the benefits of AHF is the ability to simulate a wide variety of patients, tending towards patient-specific simulations. In the near future, ways to enable multi-patient simulation despite the presence of tangible anatomy (which constrains eligible patient anatomy) will be addressed. Second, the simulator will need to be further validated by comparing performance between experts and novices during tests on various simulated patients.

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HAPTIGLIDER: A HYBRID HAPTIC INTERFACE WITH VARIABLE-FRICTION FEEDBACK FOR TRANSLUMINAL ENDOSCOPY SIMULATION

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INTRODUCTION

Haptics plays an essential role in the level of realism in VR simulation. To this date, many solutions have been proposed to render active force feedback in applications with multiple degrees of freedom. Still, achieving realistic haptic sensation in simulation is known to be challenging. This work presents a novel design of a hybrid haptic interface for transluminal endoscopy simulation. The design combines active with semi-passive force feedback based on variable friction to increase the level of haptic fidelity. The presented system is intended to be used in hysteroscopy simulation. However, its modular design and universal kinematic structure allows it to be employed in other domains, in particular domains involving constrained insertion motion, such as transluminal endoscopy.

MATERIALS AND METHODS

A. Overview of the system

The system integrates conventional active haptic feedback (AHF) with semi-passive variable-friction haptic feedback in the insertion degree of freedom for higher haptic fidelity. Figure 1 depicts the exterior view of the device. The system consists of three isolated modules: the insertion drive component (IDC) and two identical sub-modules constituting the base device component. Using a modular approach enables fast and parallel computation of kinematics as well as simplifies reconfiguration: the actual number of active and passive degree of freedoms (DoFs) can be changed without significant modifications of the design.

The base device component consists of two 5R manipulators, each moving independently in the XY plane. The end effectors (EEs) of the manipulators are connected with a rigid link via two universal joints. The resulting structure allows rendering force feedback in four DoFs (along and around X and Y axes).

The IDC is attached to the rigid link connecting the two manipulators of the base device. The IDC tracks the position of the instrument in the insertion and roll DoFs and renders *hybrid* haptic feedback in the insertion DoF. This component consists of a carriage on guiding rails equipped with two actuators, one controlling the gripper and another moving the carriage along the guiding rails with a capstan drive. The term *hybrid* in this context refers to the two components that render force feedback: the active

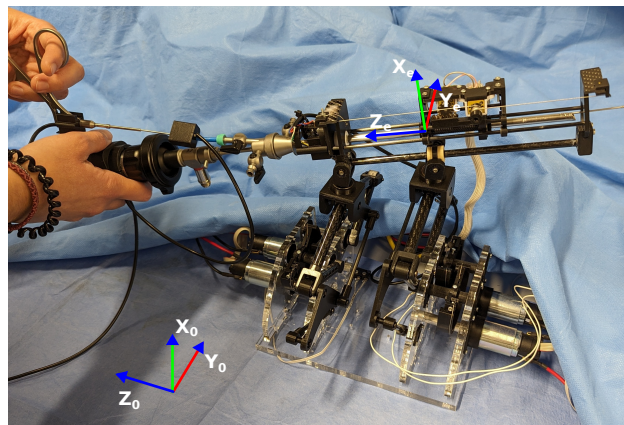


Fig. 1: The exterior view of the designed HaptiGlider haptic interface with hybrid active/variable-friction haptic feedback. Axes X_0 , Y_0 , and Z_0 define the orientation of the reference frame of the haptic interface (HI). Axes X_e , Y_e , and Z_e define the end effector frame of the HI.

capstan drive and the semi-passive gripping element. The active component generates force feedback with the capstan actuator that applies counter-force in the given DoF. The semi-passive component seeks to render haptic perception by controlling the impedance in a given DoF by adjusting the friction level. It uses a braided sleeve, the diameter of which is controlled with an actuator, to grasp the endoscope inserted in the HI and control the impedance of the passage. This approach has several advantages:

- 1) Extending the workspace of the system in the direction of insertion
- 2) Increasing the face validity of rendered feedback by using friction as the main source of force feedback, and employing AHF when static force feedback is required.
- 3) Easy exchange of instruments, even if they are (to some extent) different in diameter.

To allow free rotation of the endoscope around its longitudinal axis, the braided sleeve is attached to the carriage via supporting ball bearings allowing unhindered rotation. If necessary, this DoF could potentially also be augmented with AHF by connecting a revolute actuator via e.g. a gear or belt transmission. Previously, a similar research presented a catheter drive system based on the braided sleeve mechanism [1]. However, this system is

not a haptic interface and as such it does not feature variable friction actuation. In addition, the roll motion of the catheter is controlled by an actuator that rotates the complete platform and not the braided sleeve subsystem, which in our case is both not feasible and inefficient.

Our previous study has shown the importance of haptic feedback in the insertion DoF for in-office hysteroscopy [2]. In transluminal endoscopy, a major part of haptic feedback in this DoFs is caused by friction between the instrument and the lumen. when the endoscope is passing through the lumen, i.e. the cervical canal in the case of hysteroscopy, Thus, we hypothesise that an actuator that can passively control the level of generated friction could potentially provide a more realistic sensation. To render variable friction haptic feedback, the designed system is augmented with a semi-passive haptic element in the insertion DoF. In the past, some authors have already attempted to introduce hybrid haptic devices [3], some employing the variable-friction technology, although mostly in the task of surface interaction [4], [5]. With this work, we aim to extend its applicability by introducing the first HI for surgical simulation with hybrid active/variable-friction force feedback.

B. Variable-friction force feedback

The initial assumption for employing variable-friction force feedback was that it may be possible to characterise the relation between the insertion velocity of the endoscope, the tension applied to the braided sleeve, and the intensity of the force feedback generated to the user. Such relation could be exploited to enable rendering force feedback for any specific insertion velocity similar to what one would expect in a real hysteroscopic procedure. To assess the overall feasibility, a series of experiments was conducted using the setup depicted in Figure 2. The endoscope was attached to a fixed frame via a force sensor, while the IDC carriage, with the gripper engaged, moved along the endoscope. The results of these trials are summarised in Figure 3. These graphs demonstrate the relation between the force recorded by the force sensor and the relative force of the IDC with respect to the hysteroscope. Due to a low resolution of the encoder, the measured velocity was filtered with a low pass filter with a cut-off frequency of 10 Hz. Due to mechanical damage to the rack and pinion mechanism controlling the gripper, some recordings have a noticeable delay in the activation of force feedback, which can also be observed as a small step both in the recorded force and velocity. Nonetheless, even with the mentioned shortcomings of the setup, it is apparent from the graphs that the system demonstrated high level of repeatability across the whole spectrum of tested configurations.

CONCLUSIONS AND DISCUSSION

The presented system demonstrates the potential of employing variable-friction haptic feedback in the task of transluminal surgery. Future work will focus on integration and validation of the system and further improvement of the hybrid haptic feedback fusion.

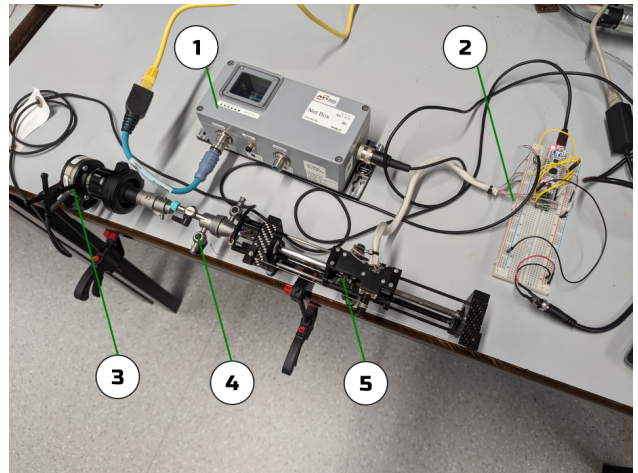


Fig. 2: The variable-friction haptic feedback analysis setup: (1) the force sensor controller, (2) the IDC controller, (3) the force sensor, (4) the endoscope, (5) the IDC.

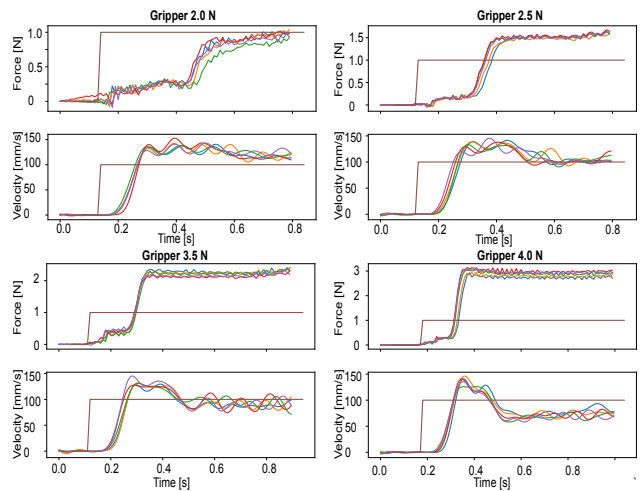


Fig. 3: Variable friction feedback step response of the IDC for five consecutive runs with linear drive generating 4.1 N, and gripper actuator generating 2.5 to 4 N. The input signal in brown is depicted in a universal scale for the visual comparison of the output signals.

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