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Multimodal Haptic Simulation for Ventriculostomy Training*

Benjamin Delbos¹, Rémi Chalard¹, Federico Di Rocco², Arnaud Lelevé¹ and Richard Moreau¹

Abstract—Freehand ventriculostomy is a frequent surgical procedure and is among the first ones that junior neurosurgery residents learn. Although training simulators exist, none has been adopted in the clinical routine to train junior residents. This paper focuses on a novel multimodal haptic training simulator that will lift the limitations of current simulators. We thus propose an architecture that integrates (1) visual feedback through augmented MRIs, and (2) a physical mock-up of the patient’s skull to (3) active haptic feedback.

I. INTRODUCTION

Ventriculostomy is one of the most frequent procedures in neurosurgery [1]. It consists in the insertion of a catheter into the brain to relieve pressure due to the accumulation of CerebroSpinal Fluid (CSF) in the ventricles. The procedure is prescribed through diagnostic imaging, which is used to evaluate the size, shape, and position of the ventricles. In many cases, patients require emergency intervention, and the Freehand Ventriculostomy (FV) technique is preferred to assisted procedures [2]. In FV, neurosurgeons blindly insert the catheter through the parenchyma, aiming for the Anterior Horn of the Ventricle (AHV). The burr-hole is placed at the Kocher’s point using external anatomical landmarks, namely the nasion, the eyeballs, the External Auditory Canal (EAC), and the coronal suture [2]. To guide their trajectory, surgeons usually aim for the foramen of Monroe, an internal structure joining ventricles [3]. In these conditions, an accurate understanding of the internal anatomy of the patient is required. Indeed, neurosurgeons need to map their mental representation of internal structures to external landmarks and thus need to combine different types of information. Proprioceptive information related to the palpation of the skull, haptic information related to the progression of the needle, and the graduation of the catheter are all taken into account to successfully puncture the ventricle. An illustration of the FV procedure is provided in Fig. 1.

Despite its high prevalence, the accuracy of the FV technique is still a controversial topic. Numerous image-assisted procedures, e.g. neuronavigation, have been proposed, but the additional efforts required are not always perceived as worth it by surgeons [4].

Even though this gesture seems simple, insufficient training causes additional trauma and increases the risk for the patients [4]. It is the first surgical act that neurosurgery junior residents are trained for, but some surveys have shown that they still need more passes than senior residents to

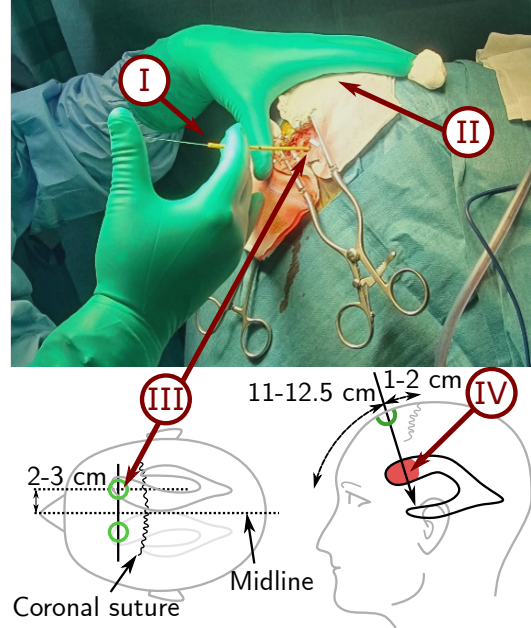


Fig. 1: Overview of the freehand ventriculostomy: (I) the catheter; (II) palpation of anatomical landmarks; (III) the burr-hole place at the Kocher’s point; (IV) the AHV.

successfully puncture the ventricle [5], highlighting the limits of current training procedures. To tackle these issues and adapt to new regulations, simulators have been developed to help in the training of ventriculostomy. We distinguish three categories of haptic simulations approaches [6] (only-computer-based simulation has been discarded as the training of such a gesture requires haptic feedback [7]):

- 1) Physical simulation (with cadavers or manikins) enables palpation of external landmarks important in ventriculostomy procedures, but suffers from low reusability and variety [6], as haptic feedback is reproduced by the insertion of a real catheter into a limited set of physical elements that wear and tear over time.
- 2) Virtual Reality (VR) based simulation, associated with Active Haptic Feedback (AHF), is not subject to the same limitations. It enables training on various anatomies [3], [8], but its important drawback is its high cost and the lack of anatomical landmarks [6].
- 3) Although Mixed Reality (MR) simulation associates physical simulation (3D-printed materials) with VR to enhance learning efficiency, it still suffers from the same downsides of material degradation over time.

Due to design compromises, these simulators all lack part of the multi-modal (visual, kinesthetic, and touch) feedback

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required in the daily practice of the FV gesture. For this reason, experienced neurosurgeons from the Hospices Civils de Lyon have not used any of the aforementioned training tools for the junior residents’ clinical practice to date.

In this paper, we introduce a ventriculostomy simulator that provides multi-modal feedback associated with AHF, virtual medical imaging, and a tangible setup. This association is unprecedented in ventriculostomy training. Rendered haptic feedback was designed from needle insertion models found in the literature. The parameters of these models could not be found in the literature and were experimentally tuned in collaboration with partner neurosurgeons.

This paper is organized as follows. Section II exposes components of the simulator and their synchronization. In Section III, force rendering of the catheter-brain interaction is discussed with experimental results introduced in Section IV.

II. MATERIAL AND METHODS

To enhance training efficiency, we propose a multi-modal simulator that permits both tangible and motorized haptic feedback and visual feedback. It features a physical manikin of a patient’s head that does not wear out, and a real catheter handled by the user to enter the manikin. They both permit palpation and dual-hand handling to provide tangible haptic and direct visual feedback. The variety of patient anatomies and tissue properties is handled by numeric simulation that renders haptic feedback through a motorized haptic device mechanically connected to the end of the catheter. The trainees can view, in real time, virtual medical imaging of the internal anatomies of the patient and the position of the catheter inside, synchronized with their gestures.

A. Tangible Haptic and Visual Feedback

To reproduce realistic interactions between the hand of the trainee and the patient’s head, a 3D-printed skull, (see Fig 5), was designed based on an arbitrary set of MRIs. It features mostly used external landmarks. To allow passage of the catheter through the manikin, the printed skull is opened behind the right eyeball and before the EAC. Although the burr-hole would typically be small enough to let the catheter pass, the aperture was made sufficiently large to allow trainees to choose different entry points, and mimic the positioning of the Kocher’s point. To replicate clinical-practice conditions, a usual graduated catheter is guided by the trainee into the skull.

B. Rendered Haptic Feedback

The minimal Degrees of Force Feedback (DoFF) required for the haptic simulation of needle insertion have not been established yet in the literature [9]. 1 to 3 DoFF could be sufficient for the simulation of a “single region”. However, 5 DoFF are advised to simulate an insertion in “arbitrary regions” [9]. To provide efficient training scenarios, by enabling the placement of the entry point and choosing the needle’s direction, we determined that at least 5 DoFF were necessary:

- 1 DoFF to render axial forces (F_A);

- 2 DoFF to render lateral forces (F_L);
- 2 DoFF for moments around orthogonal axes (moment around the shaft is not required in the FV).

A Virtuoso 6D Desktop (Haption) is chosen as haptic device, enabling 6 DoFF to render interactions between the catheter and a virtual patient brains.

C. Visual Feedback

Visual feedback consists of a direct view of the aforementioned skull and catheter. We also render diagnostic images (MRI scans) projected in the sagittal, axial, and coronal planes and sliced at a specific dynamic position. To match clinical practice, the trainees can browse through MRIs and evaluate the shape of the ventricles using a dedicated Human-Computer Interface (HCI). During the first stage of training, the trainees will also be able to visualize the current position of the catheter tip on MRI slices to stimulate their understanding of directionality and spatiality. As the trainees progress, the “interactive-time” visualization of the trajectory is removed to match clinical practice conditions.

D. Synchronization

To provide realistic and immersive simulation, the catheter-brain interaction must be consistent in every modality of the simulator. As the skull can be freely oriented by the trainee (as the head of a real patient in practice), its position and orientation are tracked using an Inertial Measurement Unit (IMU) attached to its inner side. They are expressed in the reference frame of the robot \mathfrak{R}_{Robot} .

Two different patient brains have been selected for training purposes. They are derived from real MRIs, chosen to match the printed skull (\mathfrak{R}_{Skull}). On the one hand, they are displayed on a screen, associated with the \mathfrak{R}_{MRI} frame. On the other hand, they have been segmented and rescaled to be used in a 3D collision software engine to render interaction forces by way of the haptic device connected to the catheter tip. This collision model is associated with the frame $\mathfrak{R}_{Virtual}$.

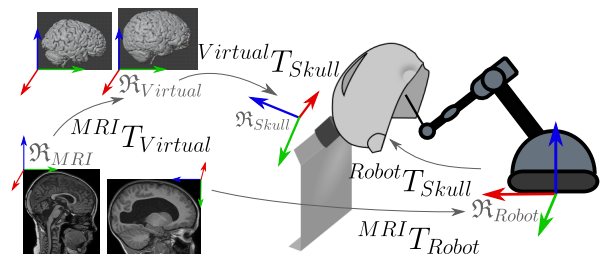


Fig. 2: Reference frames and transformations. $A T_B$ is the transformation matrix from reference frame \mathfrak{R}_A to \mathfrak{R}_B .

The consistency of these three modalities is ensured by the real-time knowledge of the transformations (depicted in Fig. 2) between each frame.

To visualize the trajectories of the catheter projected onto MRI slices, positions need to be expressed in \mathfrak{R}_{MRI} through the following transformation:

$$MRI T_{Robot} = MRI T_{Virtual} * Virtual T_{Skull} * Skull T_{Robot} \quad (1)$$

III. CATHETER INSERTION FORCE FEEDBACK

As the catheter is relatively rigid compared to the tissues, we consider its insertion to be similar to that of a needle in human tissues. Needle insertion is a ubiquitous act in medicine [9]. It is generally divided into 3 stages: (1) deformation of the tissue before puncture, (2) penetration, and (3) retraction [10]. In this work, we consider a deformation-based approach in which forces due to interaction with soft tissues are divided into three subforces [11]. As shown in Fig. 3, these components relate to anatomical layers crossed during insertion:

- At first, the catheter pushes against the outer membranes of the brain (meninges), and *stiffness forces* (\vec{f}_s) are generated as a response to elastic deformation.
- Once a predetermined force threshold is reached, the meninges breach. Then, *cutting forces* (\vec{f}_c) are applied to the tip of the catheter as it cuts the brain parenchyma.
- As the needle advances, its surface of contact with the tissues increases, thus *friction forces* (\vec{f}_f) are raising.

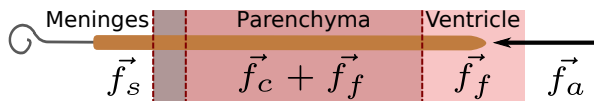


Fig. 3: Axial forces exerted on the needle during different stage of the catheter-brain interaction.

A. Stiffness force

Although in the case of a ventriculostomy, the outer layer of the meninges is cut and cauterized to facilitate passage of the catheter, the inner layers still oppose penetration. A small resistant force is thus felt before puncture, corresponding to (\vec{f}_s) in [11]. To render contact before puncture, linear functions [12], as well as polynomials [13] or exponential functions [14] have been used. As the force threshold to puncture the meninges F_r was estimated quite low (around 0.6 to 0.8 N) by expert neurosurgeons, \vec{f}_s is at first modeled using a linear spring.

B. Cutting force

The cutting of soft tissues ideally results in constant cutting forces [11]. In [13], the tracking wall algorithm is introduced to render a constant cutting force without chatter. This algorithm also reproduces the elastic behavior of soft tissues surrounding cutting interactions (*repulsion forces* [15]). According to feedback from experienced surgeons using our simulator, cutting of the brain parenchyma occurs at around 0.5 N, resulting in a constant cutting force of norm F_c during the steady-state phase of the insertion.

As soon as the tip of the needle penetrates the ventricle, the cutting force applied at the needle tip drops to zero, resulting in a sudden loss of force, which is often the signal awaited by surgeons to stop.

C. Friction force

Friction forces \vec{f}_f have been modeled using stick-slip models [11] or Lugre model [13].

Due to the high softness of the brain [16], it was assumed that static friction would induce an elastic behavior of the brain. As such, the aforementioned tracking wall algorithm has been reworked to render cutting and friction forces. This enables overcoming chatter issues in rendering friction at near-zero velocities. As described in [17], friction forces \vec{f}_f are proportional to insertion depth. In the event of a puncture of the ventricle, however, these forces are capped to a maximum value F_f as the maximum contact area with the parenchyma is reached. This value depends on the insertion depth at which the ventricle is reached.

D. Overall Forces

Pressure on the needle shaft due to the displacement of soft tissues [18] gives rise to lateral forces \vec{f}_l and moments \vec{m} , as the user strays from the insertion direction. As inspired from [19], these efforts vary with insertion depth as the needle becomes more constrained by surrounding tissues.

Thus, the global force \vec{f}_g expressed in \mathfrak{R}_{Robot} is:

$$\vec{f}_g = \vec{f}_s + \vec{f}_c + \vec{f}_f + \vec{f}_l \quad (2)$$

IV. RESULTS

Two trajectories obtained from a failed (red) and a successful (green) puncture of the ventricle are compared to the ideal trajectory (dashed line from Kocher's point to Monroe's foramen) in Fig. 4. Corresponding force profiles are plotted as a function of time in Fig 4(b), and of insertion depth in Fig 4(c). Both insertion and retraction were performed by the trainee, resulting in a closed-loop force profile in Fig 4(c). In both Fig 4(b) and (c) profiles differ due to the puncture of the ventricle in the successful attempt resulting in a sudden drop of force. Following this event, the friction force, which was increasing with depth, is capped at the value of F_f . In the failed attempt, the friction force is not capped as the needle keeps progressing into soft tissues. At an insertion depth of around 7 cm, the trainee decided to retract, as by that depth the ventricle should have already been punctured. As the needle is retracted, forces due to elastic deformation at the needle tip gradually diminish. During retraction, friction force progressively decreases as the surface of contact between the needle and the tissues decreases (see Fig. 4). Haptic parameters to render forces could not be found in the literature, as models used in ventriculostomy simulators lack clear descriptions. The values used in the current simulator were chosen according to feedback from expert neurosurgeons using this simulator. These values are illustrated in Fig. 4, and correspond to $F_r = 0.8$ N to rupture the meninges and $F_c = 0.5$ N to cut the parenchyma. The stiffness of the meninges was tuned to a value of around 133 N/m. As friction is very low in the context of FV, properties were hard to tune. At the moment, a friction coefficient of 1.6 is used, resulting in a maximum value $F_f \approx 0.1$ N at the moment of puncture. These values vary slightly between patients due to inter-patient variability.

The simulator resulting from the association of elements described in Sec. II is illustrated in Fig. 5. Currently, two

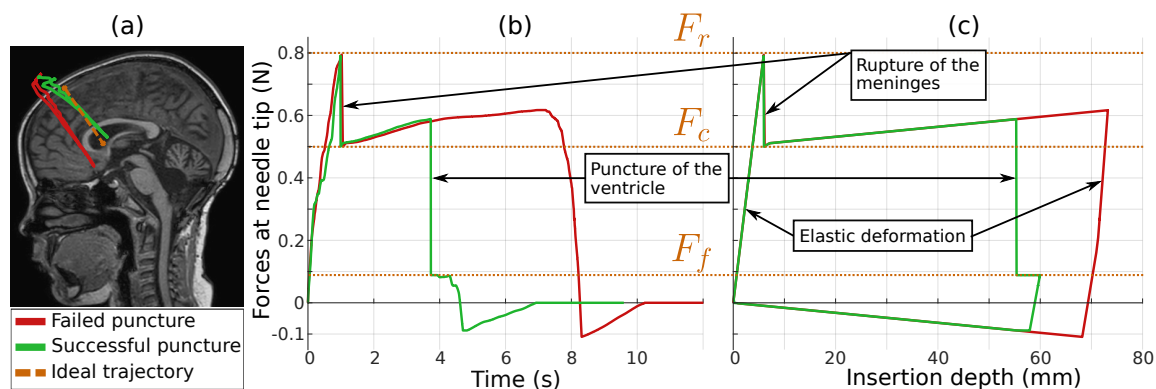


Fig. 4: Two experimental trajectories succeeding (green) and failing (red) to reach the ventricle, projected on a slice of the MRI (a). Corresponding force plots are given; (b) as a function of time, (c) as a function of insertion depth.

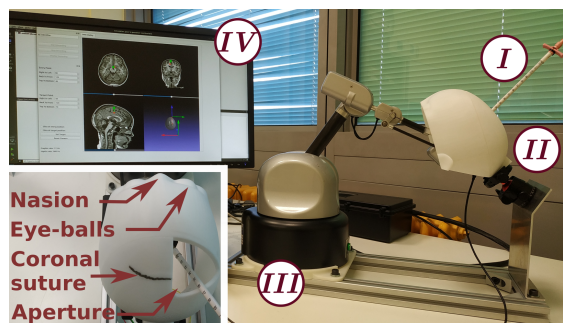


Fig. 5: Freehand Ventriculostomy Simulator: I) Catheter, II) Printed Skull, III) Haptic Device, and IV) MRI Visualization.

different patients are simulated with more or less dilated ventricles (one of them is illustrated in Fig 4).

V. CONCLUSION

Current ventriculostomy simulators fail to offer a sufficient set of feedback required to train the multi-modal technique of Freehand Ventriculostomy. In this work, a multi-modal approach is introduced, offering the trainees haptic and visual feedback using tangible elements (the catheter and patient skull) and virtual ones (synchronized medical imaging and catheter-brains interaction force feedback). The tangible elements help render realistic manual palpation and dual-hand handling of the tool, while the virtual ones bring the variability of rendered medical cases and the flexibility of customization for a richer training experience. In future works we will investigate registration algorithms to enable preoperative patient-specific simulation. The usage of more advanced force models will also be explored, in accordance with the evaluation of content, construct, and face validity of the simulator through trials with novice and expert surgeons.

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