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### ► To cite this version:

Cassandre Simon, Lucas Herfort, Flavien Lebrun, Elsa Brocas, Samir Otmane, et al.. Design and evaluation of UltRASim: An immersive simulator for learning ultrasound-guided regional anesthesia basic skills. *Computers and Graphics*, 2024, 119, pp.103878. 10.1016/j.cag.2024.01.005 . hal-04475691

**HAL Id: hal-04475691**

**<https://hal.science/hal-04475691v1>**

Submitted on 3 Apr 2024

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Preprint Submitted for review  
April 3, 2024

# Design and evaluation of UltRASim: an immersive simulator for learning ultrasound-guided regional anesthesia basic skills

Cassandre Simon<sup>a</sup>, Lucas Herfort<sup>a</sup>, Flavien Lebrun<sup>a</sup>, Elsa Brocas<sup>b</sup>, Samir Otmane<sup>a</sup>, Amine Chellali<sup>a,\*</sup>

<sup>a</sup>IBISC Lab, Univ Evry, Université Paris Saclay, Evry, 91020, France

<sup>b</sup>Anesthesiology Department, Centre Hospitalier Sud Francilien, Corbeil-Essonnes, 91100, France

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## Abstract

Virtual reality shows great promise as a technology for training healthcare professionals within a secure simulated environment. This work presents the design, development, and assessment of UltRASim: an immersive simulator for ultrasound-guided regional anesthesia. First, task and skills analyses were performed with domain experts to build the task model of the procedure and determine the simulator’s learning objectives and design constraints. Then, a face and content validity study was conducted with eighteen anesthesiologists to assess the simulator’s prototype. The responses to seven of eleven face validity questions were predominantly positive, indicating a favorable reception. The primary concerns pertained to the fidelity of haptic feedback during needle insertion. This suggests incorporating a higher fidelity haptic device in future design iterations. Conversely, responses to all six questions related to the content validity were predominantly positive. Participants found that the simulator held significant potential as a training tool, particularly for developing hand-eye coordination skills. These findings validate several design choices and highlight areas for improvement in subsequent iterations of UltRASim before its formal validation as a training tool.

*Keywords:* Immersive simulation, Medical training, Simulator fidelity, Haptic feedback, Ultrasound-guided regional anesthesia

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## 1. Introduction

The training of healthcare personnel is a critical concern within the medical field, as it directly impacts patient safety. Traditionally, training has relied on a companionship model, which combines theoretical lessons with observations of experienced practitioners, followed by hands-on practice on patients, animals, or cadavers [1, 2]. However, this approach raises ethical and patient safety issues [3, 4, 5]. Recognizing this, the French High Authority for Health published a report [6] emphasizing the importance of “never the first time on a patient”. This

led, in 2018, to significant reforms in medical studies in France, encouraging a shift towards innovative training methods that do not put patients at risk. This created an urgent need to develop simulation-based tools to support medical training.

One medical specialty significantly impacted by these reforms is anesthesiology. This field involves administering anesthesia to eliminate pain and motor reactions before surgical procedures. More precisely, regional anesthesia targets specific nerve blocks in a localized part of the body (such as the arms or legs), temporarily blocking the nerves’ ability to transmit information. The advantage is that the patient can stay awake during surgical procedures and recover faster [7]. However, this approach requires complex technical skills due to the proximity of the target nerves to vital structures such as blood vessels, organs, and the nerves themselves. Hence, incorpo-

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\*Corresponding author: Tel.: +33-1-69-47-75-33; fax: +0-000-000-0000;

Email address: amine.chellali@univ-evry.fr (Amine Chellali)



Figure 1: The user interface of UlTRASim including a head-mounted display with two tracking cameras to visualize the virtual scene and two haptic devices to control the virtual instruments. (Top left) The virtual scene as seen by the user with the virtual instruments manipulated by the user and the ultrasound screen displaying the ultrasound image.

1 rating simulation into regional anesthesia training seems  
 2 natural and essential. Additionally, ultrasound for needle  
 3 guidance in regional anesthesia has become increasingly  
 4 prevalent, leading to a high demand for training in this  
 5 imaging modality among interns and experienced practi-  
 6 tioners [8]. Thus, training guidelines have been published  
 7 to highlight the significant role of simulation in this spe-  
 8 cialty [9].

9 In this context, virtual reality (VR) emerges as a valu-  
 10 able tool for acquiring the technical skills necessary for  
 11 ultrasound-guided regional anesthesia (UGRA). VR tech-  
 12 nology has already proven effective in medical training  
 13 [10, 11, 12], as it immerses learners in realistic envi-  
 14 ronments, enables the practice of various scenarios, and al-  
 15 lows for repeated practice until skills are mastered—all  
 16 while avoiding risks for real patients.

17 However, developing these tools is challenging and po-  
 18 tentially expensive [13], with a need for more guide-  
 19 lines for their design. Additionally, their evaluation often  
 20 confuses presentation with system functionality, relying  
 21 heavily on superficial visual features that do not impact  
 22 the acquisition of target skills [14]. Therefore, adopt-  
 23 ing these technologies for training requires a rigorous de-  
 24 sign and validation approach to demonstrate that the vir-  
 25 tual simulation accurately captures the essential charac-

26 teristics of the real environment and the task to be learned  
 27 while generating realistic behaviors from learners [14].

28 This work presents the design and evaluation of Ul-  
 29 tRASim: **U**ltrasound-guided **R**egionale **A**nesthesia im-  
 30 mersive **S**imulator (Figure 1), aiming at learning basic  
 31 UGRA skills [15]. The task and skills analysis and the  
 32 system design were conducted in collaboration with ex-  
 33 pert anesthesiologists, following a user-centered approach  
 34 guided by the concept of simulator fidelity.

35 The objective of this work is twofold. First, it informs  
 36 about the UGRA practice, the learners’ needs, and the de-  
 37 sign process of UlTRASim. Second, it presents the results  
 38 of evaluating the first prototype of the system, validating  
 39 certain aspects, and guiding the next steps of its develop-  
 40 ment. The contributions of this work are as follows:

- 41 1. Presenting the task, skills analyses for the UGRA  
 42 procedure, and the design requirements of UlTRA-  
 43 Sim,
- 44 2. Designing the simulator’s components in collabora-  
 45 tion with domain experts and following guidelines  
 46 based on the concept of simulator fidelity,
- 47 3. Evaluating the face and content validity of the simu-  
 48 lator with experts and novices and extracting recom-  
 49 mendations for future design iterations.



## 2. Related Work

### 2.1. Fidelity and validity of simulators

Fidelity and validity are fundamental for evaluating and adopting simulators as training tools. We present in the following a brief review of these two concepts.

#### 2.1.1. Simulator validity

Validity refers to the degree to which a test, model, simulation, or other reproduction accurately represents its real-life counterpart [14]. For instance, a valid simulation effectively accurately represents the intended task, considering the specific learning objectives and the target population's characteristics. It is important to note that validity does not necessitate an exact replica of the real situation. Instead, the simulation should capture the essential characteristics of the task and the real environment. In the context of medical simulation, the validation process typically involves five steps [16]:

*Face validity*, an aesthetic validation based on the system appearance and its difference from the real device. *Content validity*, which assesses the accuracy and relevance of the content offered by the simulator. These two steps are carried out by experts based on a detailed system examination. *Construct validity* aims to ensure that the simulator differentiates novices' performance from that of experts. The *concurrent validity* verifies whether the simulator is equivalent to its competitors in the field. Finally, the *predictive validity* verifies that the performances obtained on the simulator are similar to those obtained in real situations. Each validation step verifies a critical aspect of the system. Therefore, the complete validation of a simulator is a slow and gradual process requiring numerous studies.

#### 2.1.2. Simulator fidelity

It is commonly accepted that, to create simulators that enable the transfer of skills to the real world, a strong connection between the simulation environment and the actual environment is necessary [17]. This introduces the concept of simulator fidelity. Considering the training objectives of a simulator, fidelity can be defined as the similarity between the skills taught in a simulator and those used in the real-world [18]. Since introducing the term fidelity, many researchers have proposed different dimensions related to this concept to evaluate their simulators.

The variety of domains and presented simulators makes a classification that encompasses all the dimensions in the literature difficult. In addition, depending on the context, certain fidelity aspects may have more or less importance for the objectives and performance of a simulator. Finally, a consensus has yet to be found to determine the exact role of simulator fidelity in medical training and, more importantly, the role of each dimension in transferring skills to the real world [13].

In this context, we will refer to the model presented by Waller and Hunt [19], which differentiates between two aspects of fidelity: interface fidelity and environmental fidelity. *Interface fidelity* is defined as the degree to which the input and output interaction devices used in the simulator operate in the same way as if the learners were interacting with the real world. This dimension is central in transferring skills to the real world [20]. It is affected by the ease of interaction and the user's level of control over the system [17]. For example, effective interaction requires that any action by the operator in the virtual environment (VE) generates an instantaneous and consistent multimodal response from the system.

On the other hand, *environment fidelity* is related to the realism of the simulation [17]. It is defined as the degree of correspondence between the real world and the simulated environment [19]. This dimension depends on a subjective judgment of similarity between these two environments rather than a quantifiable correspondence between the values of the variables. It is affected by the quality of the system's visual, auditory, and haptic rendering. However, the realism of the environment should be a means to serve the specific educational objectives of the system and not a goal of its design [21]. Thus, environment fidelity should be used to positively affect interface fidelity [13].

Although these two dimensions can be used to guide VR simulator design, there currently needs to be more specific guidelines to achieve their appropriate levels for medical simulators. While it may seem intuitive that medical skills transfer is guaranteed when the real and simulated environments are indistinguishable, effective and efficient training can still be achieved with low-fidelity simulators [22, 23]. Moreover, high-fidelity simulators are currently relatively expensive. This raises several questions. For example, how low can fidelity levels be set? What elements should be included in a simulator, and

1 should all features have the same level of fidelity? Does  
2 lower fidelity in certain aspects impact learners' perfor-  
3 mance and ability to transfer skills to real-world scenar-  
4 ios?

5 The present work does not aim to provide definitive an-  
6 swers to these questions. Nevertheless, it will rely on the  
7 existing literature on fidelity to guide the design process  
8 and the selection of elements for our simulator. To achieve  
9 this, a user-centered design approach is employed, involv-  
10 ing inputs from expert anesthetists in determining the fea-  
11 tures to be incorporated into the simulator and their cor-  
12 responding fidelity levels. Furthermore, the evaluation of  
13 the simulator will adhere to the principles of validity and  
14 follow the validation steps mentioned above. The aim is  
15 to create and validate a system that better meets the prac-  
16 titioners' needs using an evidence-based methodology.

## 17 2.2. *Simulators for medical training*

18 Medical simulators are designed to emulate various  
19 working environments, replicating specific aspects of a  
20 task or recreating an entire environment, such as an op-  
21 erating room. We will explore some of the existing liter-  
22 ature on medical simulators, emphasizing those designed  
23 for UGRA. These simulators can be divided into two fam-  
24 ilies: physical and virtual simulators.

### 25 2.2.1. *Physical simulators*

26 These simulators utilize mannequins and synthetic  
27 models that reproduce all or part of the anatomy. Their  
28 fidelity is variable according to the specific learning re-  
29 quirements.

30 High-fidelity simulators enable learners to practice en-  
31 tire procedures [24]. They often possess a high visual  
32 fidelity that can accurately mimic the human body in its  
33 entirety or certain aspects. Nonetheless, these simulators  
34 tend to be costly due to their intricate functionality, which  
35 limits their widespread utilization in training centers and  
36 teaching hospitals.

37 Low-fidelity simulators, known as part-task trainers,  
38 concentrate on specific tasks and aim to develop funda-  
39 mental technical and psychomotor skills [25]. These  
40 skills are learned separately and later integrated to per-  
41 form a complete procedure. An example of these systems  
42 is the Blue Phantom Select (Blue Phantom), utilized for  
43 acquiring basic UGRA technical skills. This simplified

44 model comprises a soft silicone tissue block containing  
45 small tubular structures representing vessels (veins, arter-  
46 ies, etc.) and nerves. Additionally, it features a fluid man-  
47 agement system that replicates blood flow when vessels  
48 are punctured. However, to simulate UGRA, this model  
49 must be used with an external ultrasound system and a  
50 needle (not included). Similar commercial models such as  
51 NYSORA simulators (NYSORA) and the TruNerveBlock  
52 (TwinMedical) and non-commercial prototypes [26, 27]  
53 have been developed.

54 Low-fidelity simulators are characterized by their low  
55 acquisition cost and offer a moderately realistic tactile and  
56 haptic experience [13, 28]. While this task-centered ap-  
57 proach is appealing, the low-fidelity simulators have sev-  
58 eral limitations. First, their reusability is limited, leading  
59 to increased long-term training costs [25, 13, 29]. The  
60 repeated insertion of needles leaves visible marks on ul-  
61 trasound images and alters the mechanical properties of  
62 the tissue, which can impede learners during subsequent  
63 practice sessions [30]. Additionally, these simulators of-  
64 fer limited scenarios and are challenging to customize for  
65 specific case studies. Furthermore, they lack objective  
66 measures to assess learners' performance, often relying  
67 on subjective evaluations by experts [31, 5]. Finally, a  
68 recent literature review reveals that physical UGRA sim-  
69 ulators frequently lack tactile sensations and realistic hap-  
70 tic feedback [1]. These drawbacks have hampered the  
71 widespread adoption, validation, and utilization of such  
72 systems [1, 32].

### 73 2.2.2. *Virtual simulators*

74 Virtual simulators use computer-generated 3D models  
75 to recreate medical environments. They often integrate  
76 physical interfaces that enable real-time control of instru-  
77 ments. The system captures changes made to the 3D mod-  
78 els and provides a suitable response to the user. Some  
79 systems incorporate haptic feedback, creating a sense of  
80 physical contact with 3D objects. This allows users to  
81 perceive the sensation of touching the 3D representation  
82 of the patient in addition to seeing it. Some simulators  
83 also combine virtual and physical elements to provide re-  
84 alistic tactile experiences [33]. Virtual simulators offer  
85 numerous advantages for medical training. They facili-  
86 tate the multiplication and customization of training ses-  
87 sions and scenarios [24], allowing for progressive diffi-  
88 culty levels. Contextualized cues can be incorporated to

1 assist learners throughout the process, and stress elements  
2 can be introduced as learners gain competence [34]. Fur-  
3 thermore, virtual simulators enable objective evaluation  
4 of performance by automatically measuring various pa-  
5 rameters [16, 5]. This allows for tailored feedback to  
6 learners regarding their performance and enables them to  
7 track their learning curves over time [11].

8 However, these technologies also have some draw-  
9 backs. While obtaining a high visual fidelity rendering is  
10 currently reasonably achievable, getting a realistic haptic  
11 rendering is far more complex [4, 24]. Additionally, the  
12 acquisition cost of these simulators is often notably high,  
13 particularly when haptic interfaces are involved [29].  
14 However, this cost can be amortized over the long run as  
15 these systems are more reusable than physical simulators.  
16 Lastly, despite the existence of validation studies, only a  
17 few simulators have been widely embraced as standard  
18 tools for medical training [35, 13].

19 Like their physical counterparts, virtual simulators can  
20 be divided into two categories: partial and full simula-  
21 tors. We will focus on partial virtual simulators that train  
22 needle insertion skills, particularly in regional anesthesia.  
23 Two aspects will be mainly discussed: the validity studies  
24 of these systems and the fidelity of their user interfaces.  
25 Needle insertion is a common medical procedure that in-  
26 volves inserting a needle into the patient’s body with or  
27 without the aid of an imaging system (e.g., MRI, CT scan,  
28 or ultrasound) to reach a target area (a tumor or an organ)  
29 and collect a sample or perform a treatment (biopsy, anes-  
30 thesia). These procedures require good hand-eye coordi-  
31 nation, three-dimensional spatial abilities, and haptic per-  
32 ception skills [36]. Several virtual simulators for needle  
33 insertion training have been proposed [37, 38, 30, 39].  
34 The reader can refer to two recent literature reviews on  
35 this topic [40, 41].

36 Several virtual systems have been explicitly proposed  
37 for regional anesthesia training. For example, Bibin et  
38 al. [42] developed SAILOR, a virtual simulator for re-  
39 gional anesthesia. The simulator incorporates realistic vi-  
40 sual rendering, simple interactions using the mouse to ma-  
41 nipulate the needle, and a pseudo-haptic effect when inter-  
42 acting with tissues. Ulrich et al. [43] presented RASim, a  
43 regional anesthesia virtual simulator based on a 3D stereo-  
44 scopic screen displaying the tools and the concerned limb  
45 and a haptic arm allowing manipulation of the virtual nee-  
46 dle. Grottke et al. [44] utilized a comparable interface in

47 their regional anesthesia simulator, featuring the creation  
48 of personalized scenarios by using patient-specific data.  
49 These systems have only undergone preliminary subjec-  
50 tive evaluations, and no studies have been published re-  
51 garding their validity [45]. In addition, the previous sys-  
52 tems used external monitors where the 3D scene is shifted  
53 from the user’s action space. This could impact the acqui-  
54 sition of hand-eye coordination skills during task perfor-  
55 mance. Indeed, some studies showed that indirect vision  
56 with translational misalignment between the motor space  
57 and the visual space has a negative impact on hand-eye  
58 coordination [46, 47, 48]. Other studies showed that co-  
59 localization of hands and tools controlled by the user im-  
60 proves manipulation task performance in VR [49, 50, 51].  
61 Finally, these systems do not include a simulation of ultra-  
62 sound to guide the needle insertion, which limits their use  
63 to train procedures complying with the recommendations  
64 of scientific societies of anesthesiology [9].

65 In contrast, there have been limited VR systems de-  
66 signed explicitly for training ultrasound-guided needle in-  
67 sersion procedures [45, 52]. Vidal et al. [53]. introduced  
68 a VR simulator to facilitate ultrasound-guided punctures  
69 in interventional radiology. The user interface features a  
70 stereoscopic monitor displaying a 3D view of the targeted  
71 limb and two haptic arms for manipulating the virtual nee-  
72 dle and the ultrasound probe. Face and content validity  
73 studies were conducted [54]. However, the evaluations  
74 were limited to novice users, limiting the comprehensive  
75 assessment of its validity. Alamilla-Daniel et al. [55]  
76 proposed a VR simulator for ultrasound-guided interar-  
77 ticular infiltration, comprising two haptic arms to control  
78 the probe and the needle and a basic computer monitor for  
79 visualizing the VE. However, a user study has yet to be  
80 conducted to evaluate this system. Recently, Chuan et al.  
81 [56] have designed an immersive simulator for UGRA.  
82 The user interface includes an HMD for the visualization  
83 of the 3D scene. In addition, the system comes with a low-  
84 fidelity user interface since it uses Hand-held controllers  
85 to manipulate the needle and the ultrasound probe, and no  
86 haptic feedback is included. The system was evaluated for  
87 construct validity and could differentiate the performance  
88 of novices and experts.

89 The previous review demonstrates that partial simula-  
90 tors, whether physical or virtual, are more suitable than  
91 full simulators for learning basic technical skills. Physi-  
92 cal simulators are affordable but come with several lim-

1 itations. While virtual simulators provide an interesting  
2 alternative to overcome some of these limitations, exist-  
3 ing systems incorporate interfaces with low to moderate  
4 levels of fidelity. Moreover, very few systems combine  
5 ultrasound with needle insertion, which is highly recom-  
6 mended for regional anesthesia procedures and is cur-  
7 rently considered the standard of care for peripheral nerve  
8 blocks [57]. Finally, only a limited number of validation  
9 studies have been conducted on these systems. Therefore,  
10 it appears necessary to go beyond the existing solutions by  
11 introducing a new VR simulator for UGRA. The proposed  
12 approach incorporates the concept of interface fidelity to  
13 overcome the existing systems' limitations and follows a  
14 rigorous evaluation process to validate the different sys-  
15 tem components progressively.

16 In the following, we present the design process of our  
17 system, starting from the task and skills analysis and con-  
18 cluding with the system evaluation by domain experts.

### 19 3. Task and skills analysis

#### 20 3.1. Task analysis

##### 21 3.1.1. Analysis method

22 To follow user-centered design principles, the first step  
23 was to build the task model. Task analysis provides a bet-  
24 ter understanding of how users move from goals to tasks  
25 and then actions. Thus, this analysis aims to highlight all  
26 the tasks performed to understand better how the whole  
27 procedure is performed and how it should be simulated.  
28 This analysis divides the procedure into steps, tasks, and  
29 sub-tasks. The combination of all the steps achieves the  
30 main objective of the procedure. Steps only occur once.  
31 Tasks are actions that are combined to achieve the goal of  
32 the step. They can occur several times during the same  
33 step. Tasks are made up of sub-tasks, ~~more defined~~. Sub-  
34 tasks can appear multiple times within a single task and  
35 can be decomposed into more basic actions. Steps, tasks,  
36 sub-tasks, and actions are hierarchical. Tree diagrams  
37 can therefore represent their order and structure. Thus,  
38 a hierarchical decomposition tree describing the Hierar-  
39 chical Task Analysis (HTA) of the UGRA procedure at  
40 these different levels of detail was generated using the  
41 mental mapping software Xmind (XMIND LTD, version  
42 22.09.3168).

43 The task model was produced using data from the liter-  
44 ature, educational videos, and macroscopic observations  
45 carried out in the field. First, ten public videos with a to-  
46 tal duration of 49 min were viewed. These videos show  
47 the performance of UGRA of the sciatic nerve and the  
48 femoral nerve. The analysis of these videos provided a  
49 first insight into UGRA and helped identify the basic steps  
50 the practitioner must follow to perform it.

51 The second step involved referring to a specific docu-  
52 ment designed for interns, which provided detailed in-  
53 structions for performing UGRA procedures, specifically  
54 targeting the sciatic nerve, femoral nerve, and brachial  
55 plexus [58]. The information provided in this docu-  
56 ment complemented and enhanced the notes taken from  
57 the videos.

58 Finally, a total of 42 cases performed by expert anesthe-  
59 siologists were observed. A thinking-aloud method [59]  
60 was used to have details on the tasks performed. Once all  
61 the data was grouped, the task model was generated using  
62 Xmind.

##### 63 3.1.2. Validation method

64 The first validation step took place during the weekly  
65 meeting of the partner anesthesia department. This meet-  
66 ing brought together ten expert anesthesiologists. Dur-  
67 ing this one-hour validation session, the diagram was dis-  
68 played on a large screen to the anesthesiologists, who  
69 were encouraged to provide unrestricted feedback on the  
70 model's alignment with their practice. As a result, this  
71 real-time feedback enabled the comparison of practices  
72 between experts, highlighting the value of this approach  
73 in generating a universal model for UGRA procedures.

74 Following this first validation phase, modifications  
75 were made to the task model based on experts' feedback.  
76 Most of these changes were related to terminology adjust-  
77 ments. The final validation was done remotely due to the  
78 busy schedule of the anesthesiologists. For that purpose,  
79 the diagram was sent by email accompanied by an on-  
80 line demographics and validation questionnaire, allowing  
81 to specify the profile of the respondents as well as their  
82 opinion on the validity of the model.

##### 83 3.1.3. Results

84 Among the ten anesthesiologists present during the  
85 first validation session, only eight responded to the final  
86 validation questionnaire (six men and two women, with

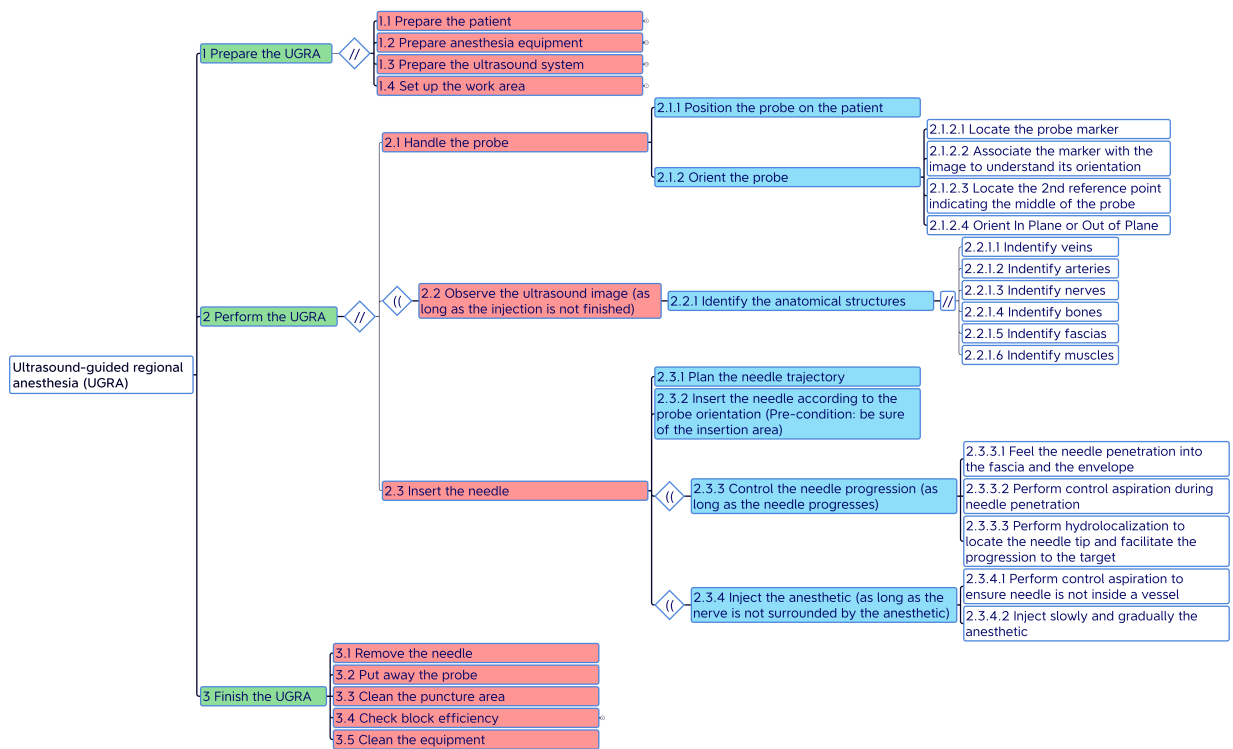


Figure 2: The task model of UGRA at the step (green), task (pink), sub-task (blue), and action (white) levels. Sub-tasks and actions are exposed only for step 2 (pointed out as the most relevant for the system design). The “//” symbol indicates parallel tasks while the “((” symbol indicates iterative tasks (loops).

1 13.12± 8.33 for the average number of years of practice and 675±353 cases of UGRA achieved on average).  
2 The hierarchical decomposition of the UGRA procedure  
3 is presented in (Figure 2). All the involved expert practitioners  
4 validated it.

5  
6 Among the various UGRA procedures, we decided, in  
7 consultation with expert anesthesiologists, to focus the  
8 simulator’s design on the femoral nerve block (FNB) scenario.  
9 FNB involves injecting an anesthetic agent around  
10 the femoral nerve to provide analgesia to the anterior aspect  
11 of the thigh, knee, and proximal tibia. FNB can be  
12 used for postoperative anesthesia or analgesia in various  
13 lower limb surgeries, ranging from femoral neck fracture  
14 fixation to total knee replacement. Hereafter, we describe  
15 the FNB using our task model.

16 The FNB consists of three main steps broken down into  
17 tasks, sub-tasks, and actions. The first step is to **prepare**  
18 **the UGRA** by positioning the patient and preparing the  
19 area to be anesthetized while ensuring compliance with  
20 hygiene rules. This step also includes preparing the equipment  
21 to be used. The equipment comprises an ultrasound  
22 scanner with a 5-10 MHz frequency linear probe, a 22-  
23 gauge, and a 5-centimeter needle. The second step is to  
24 **perform the UGRA**. It includes manipulating the probe  
25 on the surface of the patient’s skin to observe and locate  
26 anatomical structures while inserting the needle. The  
27 structures to be identified include the artery, which is characterized  
28 by slight pulsations, and the femoral vein, which collapses  
29 under the pressure applied by the probe on the skin. The  
30 nerve is located just to the right of the artery and appears  
31 as a bright oval-shaped hyperechoic structure. Once located,  
32 the anesthesiologist inserts the needle (the target depth is  
33 between 2 and 4 centimeters in an adult) in the ultrasound  
34 plane (In-plane approach). In this approach, the entire  
35 needle is visible on the ultrasound as a straight line. An  
36 out-of-plane approach, where the needle is represented on  
37 the ultrasound as a single white dot, is also possible. When  
38 the needle reaches the nerve junction point, the practitioner  
39 can inject the anesthetic and observe its distribution around  
40 the nerve. When applied to the nerve tissue, this substance  
41 can block nerve conduction. It should be noted that the  
42 needle must be inserted above and below the nerve without  
43 touching it to avoid causing damage. The last step is to  
44 **finish the UGRA** by removing the needle and probe and  
45 cleaning the puncture area and the equipment.  
46

## 3.2. Skills analysis 47

### 3.2.1. Analysis method 48

49 This step aimed to identify the skills required to perform  
50 UGRA. Once identified, the skills can be associated with  
51 the task needed to perform the procedure and then classified  
52 according to the relevance of their learning through the  
53 simulator. This can permit us to choose those to be targeted  
54 by the simulator and define the learning objectives of the  
55 system. For that purpose, a review of the literature was first  
56 carried out. After that, a focus group was organized with  
57 the same eight experts who participated in the validation  
58 session. During this two-hour session, the anesthesiologists  
59 had to associate the skills with the tasks previously  
60 identified and assess the importance of acquiring them  
61 through the immersive simulator.

### 3.2.2. Results 62

63 According to the recommendations of the American Society  
64 of Regional Anesthesia and Pain Medicine and the European  
65 Society Of Regional Anaesthesia and Pain Therapy Joint  
66 Committee, [9], the skills needed to master the UGRA can  
67 be divided into four groups: (1) understanding the  
68 ultrasound bases and handling the equipment, (2) optimization  
69 of the ultrasound image, (3) interpretation of the ultrasound  
70 image and, (4) introduction of the needle and injection of  
71 the anesthetic solution. During the focus-group session,  
72 the experts pointed out that the skills related to step 2  
73 (Perform the UGRA) are the most difficult to acquire and  
74 require the most extended learning curve. Thus, we have  
75 focused only on this step, the related tasks, sub-tasks,  
76 and the associated skills. Subsequently, only the last three  
77 skill groups were incorporated into the next phase, which  
78 consists of associating the sub-tasks with the skills. The  
79 results are presented in Table 1.

80 The experts then classified the skills according to their  
81 complexity and, thus, the relevance of their learning using  
82 the simulator. *Coordination of hand and eye movements*  
83 was considered the most complex to acquire. It is required  
84 while performing the three parallel tasks: 2.1 Handling the  
85 probe, 2.2 Observing the ultrasound image, and 2.3  
86 Inserting the needle. Consequently, this skill was chosen  
87 as the primary training objective of our simulator. The  
88 remaining skills were judged necessary. They were  
89 classified as secondary training objectives of the simulator.  
90 The subsequent design process focused on those skills

1 and their associated sub-tasks from step 2 (perform the  
2 UGRA).

### 3 **4. Design of the simulator**

#### 4 *4.1. Design method*

5 To guide the design of the system components, two  
6 dedicated focus group sessions (of two-hours each) were  
7 organized with two experts among those participating in  
8 the primary sessions. The recommendations from the liter-  
9 ature also guided the design choices. In the following,  
10 we describe the various simulator components' choices  
11 and their fidelity levels.

#### 12 *4.2. Design choices*

##### 13 *4.2.1. Interaction techniques and user interface*

14 The initial decisions revolve around selecting interac-  
15 tion techniques and interfaces to be incorporated into the  
16 simulator. To simulate the chosen UGRA tasks (i.e., tasks  
17 and sub-tasks of Step 2), the system must enable users to  
18 perform the following interactive tasks (sub-task numbers  
19 are extracted from Table 1):

- 20 1. Visualize the VE from different perspectives (to ob-  
21 serve the ultrasound screen, the needle, and the  
22 probe): required to perform all the sub-tasks of step  
23 2,
- 24 2. Manipulate the ultrasound probe: required to per-  
25 form sub-tasks 2.1.1, 2.1.2, 2.3.2, and 2.3.3,
- 26 3. Manipulate the anesthesia needle: required to per-  
27 form sub-tasks 2.3.2 and 2.3.3,
- 28 4. Inject the anesthetic: required to perform sub-task  
29 2.3.4,
- 30 5. Change the ultrasound image scale (zoom-in/zoom-  
31 out): this is achieved in the “prepare the ultrasound  
32 system” task related to step 1 (Figure 2) but is a pre-  
33 requisite to perform sub-tasks 2.2.1 and 2.3.1.

34 As mentioned above, the VR simulator should priori-  
35 tize a high level of fidelity for interactions that directly  
36 contribute to the acquisition of the primary learning ob-  
37 jectives [13]. Consequently, we have attributed a high de-  
38 gree of interface fidelity to the first three interaction tasks  
39 directly related to the defined primary skill “Coordinated  
40 eye and hand movements” associated with orienting the

41 probe (sub-task 2.1.2) and controlling the needle progres-  
42 sion (sub-task 2.3.3). On the other hand, interaction tasks  
43 4 and 5 were deemed less critical for developing this skill.  
44 Therefore, lower-fidelity interactions, involving clicks on  
45 physical buttons were used to accomplish them.

46 Thus, two haptic arms were chosen to manipulate the  
47 probe and the needle, one per instrument. Using haptic  
48 arms allows the user to have a natural grip and to manip-  
49 ulate the instruments over 6 degrees of freedom (DoF).  
50 The generated movements are closer to the real situation  
51 than joysticks or a mouse, for instance. Haptic arms also  
52 provide force feedback related to the interaction of the  
53 instruments with the tissue. Indeed, several studies have  
54 stressed the importance of this feedback for learning tech-  
55 nical skills in medicine [60, 61, 62].

##### 56 *4.2.2. Haptic and visual rendering*

57 To ensure a realistic and effective user experience, as  
58 well as the acquisition of the skills of group 2, the haptic  
59 feedback on the ultrasound probe must allow the user to  
60 smoothly slide it on the skin surface to achieve proper po-  
61 sitioning and select the appropriate approach (in-plane or  
62 out-of-plane). The probe pressure on the skin must also  
63 generate vein deformation.

64 Realistic haptic feedback during needle penetration  
65 into the body is crucial to acquiring needle manipula-  
66 tion skills. Once the skin's surface is punctured, the nee-  
67 dle moves in one direction, allowing slight adjustments  
68 through small rotations around the insertion point (yaw  
69 and pitch). The user also needs to feel the needle passing  
70 through various tissue layers.

71 For visual rendering, a VR headset was chosen to im-  
72 merse the user in the VE, which includes the patient and  
73 the ultrasound screen. This setup enables the user's vir-  
74 tual hands to align perfectly with their real hands fol-  
75 lowing the recommendations derived from the literature  
76 [46, 47, 49, 50, 51] to support the acquisition of hand-eye  
77 coordination skills. Experts advise learners to position the  
78 ultrasound screen in front of themselves, ensuring that the  
79 needle, probe, and screen remain within their visual field.  
80 Using a monitor instead of a headset would have created  
81 a discrepancy between the user's real hands and the vir-  
82 tual instruments displayed. Furthermore, the VR headset  
83 allows users to naturally change their point of view (inter-  
84 action task 1) simply by moving their heads.

### 4.2.3. Content of the virtual environment

As per the recommendations in the literature [10, 13], the level of environment fidelity can be moderate. Furthermore, the anesthesiologists commented that, during needle insertion, they focus mainly on the ultrasound screen and do not look at the patient’s body. Hence, like partial physical simulators, the virtual scene included only a cuboid representing a patient’s knee, the primary working area during the FNB. However, this representation needed to have three essential structures: the femoral nerve, the femoral artery, and the femoral vein to ensure a realistic anatomical simulation, thus helping to practice the third skills group (image interpretation).

In addition, no user’s virtual hands were included, as suggested in the literature [63, 64]. Instead, we simulated the instruments (needle and probe) they manipulate. Experts’ feedback supported this choice, as they admitted not focusing on their hands during needle insertion.

Lastly, to create a more immersive experience, the virtual scene incorporated a hospital bed on which the cuboid was placed, along with a 3D model of an ultrasound screen. Ambient operating room sound was also added as background noise in the simulation.

## 5. Simulator Development

### 5.1. Virtual Environment

The simulator was running on a laptop with an Intel Core i7 processor at 2.2GHz, 16GB of RAM, and an Nvidia GeForce GTX 1070Ti graphics card with 8GB of RAM. We used an Oculus Rift headset with a resolution of 1080x1200 per eye at 90 Hz and two tracking cameras to visualize the 3D scene (Figure 3).

We used Unity 3D (2019.4.2f1) with the SteamVR plugin to develop the system prototype. The virtual scene consisted of a cuboid containing three cylinders representing the femoral nerve, artery, and vein, respectively (Figure 4). We positioned an ultrasound screen in front of the user (Figure 1). Additionally, realistic 3D models of an ultrasound probe and an anesthesia needle were integrated into the scene (Figure 1).

To simulate the ultrasound image, we used an orthographic camera linked to the virtual probe’s movements, positioned to capture the interior of the cuboid perpendicularly to the probe (Figure 4). We used shaders to configure the visual rendering and obtain a 2D cross-section of



Figure 3: The virtual scene with the cuboid laying on the hospital bed

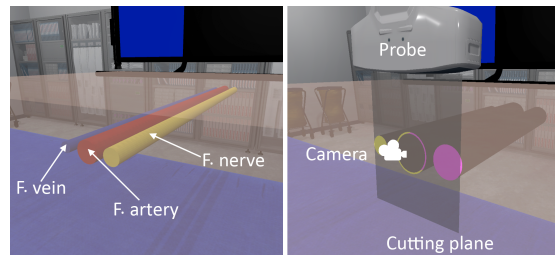


Figure 4: The cuboid (in transparency) included three tubes representing the anatomical structures. An orthographic camera and a cutting plane at the position of the probe were used to render the ultrasound image.

the intersected 3D objects (Figure 4). The resulting image was transformed into a grayscale. Finally, we applied dynamic Perlin noise [65] to the texture to achieve an appearance resembling that visualized on an ultrasound system. The image allowed visualization of the three anatomical structures and the needle (Figure 1).

### 5.2. Haptic interactions and rendering

We used two Geomagic Touch haptic arms (3D Systems Inc.) with the Kirurobo open-source plugin<sup>1</sup> for instrument manipulation. These arms enable movements in 6 DoF (translation and rotation along x-y-z axes) and provide force feedback in 3 DoF (translation along x-y-z axes). Each device has a 160 width x 120 height x 70 depth mm workspace. We used the two buttons of the left haptic arm to adjust the scale of the ultrasound image. We also used one of the buttons on the right arm to trigger the anesthetic injection.

<sup>1</sup><https://github.com/kirurobo/ManagedPhantom>



1 The ultrasound probe must maintain continuous contact  
 2 with the skin surface and exert pressure during movement.  
 3 To achieve this, we have implemented two forces: friction  
 4 force and Hooke's force.

5 The friction force is generated as the probe slides across  
 6 the skin surface and is calculated as follows:

$$\begin{cases} 0 & \delta \leq d_i \\ \lambda\delta^n + \mu\dot{\delta}\delta^n & d_i < \delta \leq d_j \\ 0 & \delta > d_j \end{cases} \quad (1)$$

7 Here,  $\lambda$  represents the unknown contact stiffness,  $\mu$  de-  
 8 notes the unknown damping coefficient,  $n$  is the unknown  
 9 Hertzian compliance coefficient,  $d_i$  (the bottom) and  $d_j$   
 10 (the top) denote the positions of the tissue surface, and  
 11  $\delta(t)$  represents the skin's local deformation:

$$\delta(t) = x - x_t \quad (2)$$

12 Where  $x_t$  represents the initial vertical position of the  
 13 skin and  $x$  is the current position.

14 Hooke's force is generated when the probe applies pres-  
 15 sure to the skin and can be expressed as:

$$f_h = -kx \quad (3)$$

16 Where  $k$  is the skin stiffness, and  $x$  is the penetration vec-  
 17 tor.

18 The value of Hooke's force is also used to deform the  
 19 femoral vein under the pressure of the probe on the skin.

20 In contrast to the probe, the needle must be capable of  
 21 penetrating the skin. Once inside, it only translates along  
 22 its penetration axis and can rotate around this same axis  
 23 (roll axis) or around the insertion point (pitch and yaw  
 24 axes; Figure 5).

25 The needle insertion force comprises stiffness, friction,  
 26 and cutting forces [66]:

$$F(x) = f_s(x) + f_f(x) + f_c(x) \quad (4)$$

27 Here,  $x$  represents the position of the needle tip,  $f_s$  is  
 28 the stiffness force,  $f_f$  is the friction force, and  $f_c$  is the  
 29 cutting force.

30 The stiffness force is generated prior to skin puncture  
 31 (calculated using the same formula as for the probe). The  
 32 friction force only occurs within the tissue and depends  
 33 on its stiffness:

$$\begin{cases} 0 & x \leq d_0 \\ (f_0 + b_0)e^{a_0(x-d_0)} + b_0 & d_0 \leq x \leq d_1 \\ (f_1 + b_1)e^{a_1(x-d_1)} + b_0 & x > d_1 \end{cases} \quad (5)$$

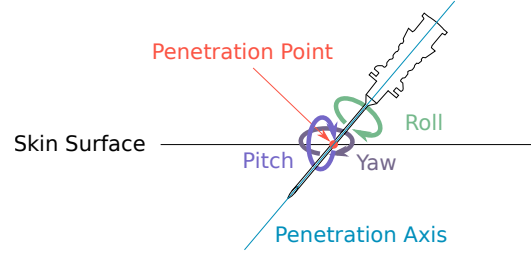


Figure 5: Needle's behavior inside the skin. It can be translated along its penetration axis, rotated around it (roll), or around the insertion point (pitch and yaw)

Here,  $d_0$  represents the initial position of the tissue,  $d_1$  is the perforation position, and  $f_0, f_1, a_0, a_1, b_0, b_1$  are parameters dependent on the mechanical properties of the tissue.

The cutting force allows the needle to slice through the tissue. It is a constant force dependent on the compliance of the tissue and is not related to the depth of the needle in the tissue:

$$f_c = c \quad (6)$$

Lastly, due to the constraints imposed by the 3DoF force feedback haptic arm, we did not apply any force to the needle when it rotated around the insertion point.

## 6. User Study

The objective of the user study was to validate the face and content of UltRASim. For that, two questionnaires inspired by studies validating other VR simulators [30, 67, 68] were used.

The face validity questionnaire consists of 11 questions (Table 2), while the content validity questionnaire consists of 6 questions (Table 3). Both questionnaires use a 5-point Likert scale. The study aimed to determine to what extent field professionals appreciate the appearance and content of the simulator.

### 6.1. Participants

We conducted this study in the partnering hospital's anesthesia and intensive care department. Eighteen anesthesiologists (11 males, seven females, one left-handed, 17 right-handed) aged 32 to 69 years ( $44.16 \pm 11.28$  years) participated in the study. All of them had minimal

1 experience with VR and haptics and rarely played video  
2 games. They were divided into two groups based on their  
3 expertise level in performing UGRA (as self-declared): 7  
4 experts (including two females) and 11 novices (includ-  
5 ing five females). The Research Ethics Committee of the  
6 Université Paris Saclay approved the study.

## 7 6.2. Experimental Procedure

8 An experimental session lasted, on average, 20 min-  
9 utes per participant. Upon arrival, the participants were  
10 required to read and sign the consent form and complete  
11 a demographic questionnaire. Subsequently, the experi-  
12 menter explained the procedure and introduced the simu-  
13 lator. The participants were then instructed to settle com-  
14 fortably, wear the VR headset, hold the haptic arms, and  
15 freely explore the system (Figure 1).

16 After that, the test of the simulator began. Participants  
17 were instructed to insert the needle using the ultrasound  
18 image guidance following the FNB scenario. To do so,  
19 they had to explore the virtual body and locate the femoral  
20 nerve while identifying adjacent structures. Then, they  
21 had to choose an entry point and insert the needle in align-  
22 ment with the ultrasound image plane (following an in-  
23 plane approach). Once near the nerve, they were required  
24 to inject the anesthetic and observe its spread around the  
25 nerve. The diffusion is calculated based on the needle's  
26 position relative to the nerve and the quantity of injected  
27 anesthetic. The test would conclude when the participant  
28 removed the needle from the virtual body. Participants  
29 were not required to complete the entire procedure, as  
30 the primary objective was to obtain subjective feedback  
31 on the appearance and content of the simulator. Immedi-  
32 ately after completing the test, participants were asked  
33 to respond to the face and content validity questionnaires.  
34 They were then encouraged to provide additional com-  
35 ments or suggestions regarding their experience and po-  
36 tential improvements to the current prototype.

## 37 6.3. Results

### 38 6.3.1. Face Validity

39 Answers to the face validity questionnaire are summa-  
40 rized in (Figure 6, left panel). Although feedback from  
41 experts (37.66% of responses scoring above 3 and 27.27%  
42 of responses scoring below 3) was generally more positive  
43 than that of the novices (31.40% of answers scoring above

44 3 and 39.66% of responses scoring below 3), no statisti-  
45 cal difference was observed between the average scores of  
46 the two groups ( $3.11 \pm 0.97$  for experts,  $2.88 \pm 1.16$  for  
47 novices).

48 The lowest scores ( $2.45 \pm 1.12$  for novices and  $2.57 \pm$   
49  $0.97$  for experts) were obtained for question Qf10 (realism  
50 of haptic feedback for the needle). Novices rated ques-  
51 tions Qf3 (realism of the ultrasound interface) and Qf8  
52 (realism of haptic feedback on the probe) higher ( $3.27 \pm$   
53  $0.90$  and  $2.81 \pm 1.07$ , respectively) than experts ( $2.85 \pm$   
54  $0.69$  and  $2.71 \pm 1.25$ , respectively). Conversely, experts  
55 rated questions Qf5 and Qf6 (handling of the haptic arm),  
56 Qf7 (probe movement), and Qf9 (consistency of needle's  
57 visual movements) higher ( $3.42 \pm 0.97$ ,  $3.42 \pm 0.78$ ,  $3.42$   
58  $\pm 1.13$ ,  $2.85 \pm 0.89$ ; respectively) than novices ( $2.72 \pm$   
59  $1.01$ ,  $2.72 \pm 1.19$ ,  $2.82 \pm 1.07$ , and  $2.72 \pm 1.36$ ; respec-  
60 tively). The highest scores were obtained for questions  
61 Qf1 (realism of the VE) for experts ( $3.71 \pm 0.75$ ) and Qf4  
62 (realism of vein deformation) for all participants ( $3.36 \pm$   
63  $1.02$  for novices and  $3.57 \pm 0.97$  for experts). The remain-  
64 ing questions received moderate scores, but the average  
65 was above 3.

### 66 6.3.2. Content Validity

67 The responses to the content validity questionnaire are  
68 summarized in (Figure 6, right panel). While the feed-  
69 back from experts (66.66% of answers with a score above  
70 3 and 7.14% of responses with a score below 3) was gen-  
71 erally more favorable compared to novices (59.09% of re-  
72 sponses with a score above 3 and 12.12% of answers with  
73 a score below 3), no statistical difference was observed  
74 between the average scores of the two groups ( $3.97 \pm 0.97$   
75 for experts,  $3.57 \pm 1.03$  for novices).

76 All questions received an average score above 3 for  
77 novices and experts. The lowest score pertains to question  
78 Qc3 (Adequate simulator for UGRA training), with an av-  
79 erage score of  $3.0 \pm 1.00$  for experts and  $3.09 \pm 0.94$  for  
80 novices. The remaining questions obtained higher mean  
81 scores, particularly among experts, notably achieving a  
82 score of  $4.71 \pm 0.75$  for question Qc1 (Promising training  
83 tool) and  $4.42 \pm 0.78$  for question Qc2 (Simulator suitable  
84 for hand-eye coordination development).

### 85 6.3.3. Free Comments

86 After completing both questionnaires, participants pro-  
87 vided verbal feedback on their experience with the simu-

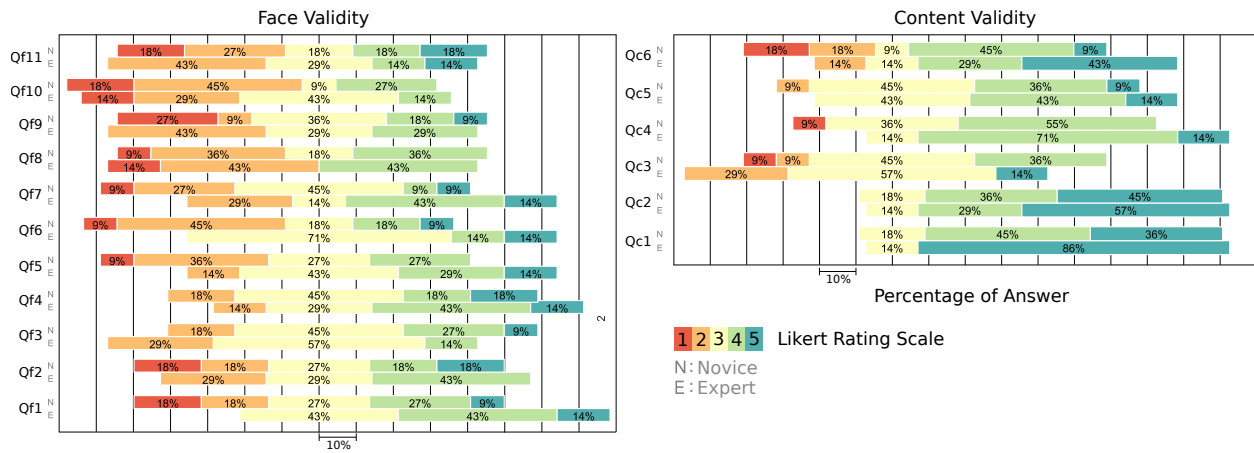


Figure 6: Percentages of respondents by score and by question for the face (left) and content (right) validity questionnaire. For each question, the answers of novices (top line) and experts (bottom line) are displayed separately.

1 lator and potential improvements to the current prototype.  
2 In the following, we summarize the most frequent comments.  
3

4 First, several participants reported lacking support for  
5 their arms while manipulating the haptic arms, leading to  
6 increased fatigue and reduced movement precision. The  
7 experts also noted that the force amplitudes felt during  
8 lateral movement of the probe on the skin (probe friction  
9 force) were too weak compared to reality. Additionally,  
10 although the force feedback of the needle before and during  
11 skin penetration (stiffness force and cutting force) was  
12 satisfactory, several participants mentioned that its amplitude  
13 was too weak once the needle penetrated the skin's  
14 surface (friction force), resulting in excessively rapid and  
15 less precise movements.

16 Lastly, participants suggested potential system improvements.  
17 For instance, they proposed offering the possibility to  
18 reverse the positions of the probe and the needle, allowing  
19 to use the simulator for training procedures other than regional  
20 anesthesia. The experts also recommended the possibility of  
21 using the needle to slightly move the nerve, enhancing precision  
22 during the injection of the anesthetic.  
23

## 24 7. Discussion and design implications

25 Our work has aimed to present the design and evaluation  
26 of UltrASim, an immersive simulator for training

basic UGRA skills. Our system stands out for its user interface  
27 design choices, aimed at increasing its fidelity to support the  
28 learning of hand-eye coordination skills.  
29

30 For that, field studies and collaborative design sessions  
31 with domain experts have permitted us to build a task model,  
32 identify the skill set necessary to perform the entire UGRA  
33 procedure and classify the skills depending on the relevance of  
34 learning them through the immersive simulator. This approach  
35 was essential to define the system's primary and secondary  
36 learning objectives and the fidelity levels of its components.  
37 This guided the design of the simulator's first prototype.  
38

39 The user study aimed to assess this prototype's face and  
40 content validity. Although these two aspects typically require  
41 validation from domain experts [16], we also found it  
42 valuable to involve novices. This decision aimed to  
43 increase the sample size and gather feedback from end  
44 users.

45 From a global perspective, 7 out of the 11 questions regarding  
46 face validity received positive responses (with an average score  
47 above 3). Over 60% of participants found the realism of the  
48 VE and the ambient sound satisfactory. However, the visual  
49 rendering of the ultrasound screen appeared to be less  
50 convenient for experts (only one expert rated it above 3).  
51 This could be attributed to its minimalist information, including  
52 the ultrasound image, zoom level, and injected product level.  
53 The quantity of the injected product was displayed on the  
54 virtual US monitor. This

1 may have been unsettling for experts used to more com-  
2 prehensive information on such interfaces. In contrast,  
3 novices seemed less disturbed, likely due to their limited  
4 expertise in using these systems. Discussing with experts  
5 could help determine the most relevant information to dis-  
6 play on this screen.

7 In addition, 44% of participants (including 57% of ex-  
8 perts) were satisfied by the rendering of vein deformation  
9 under the probe pressure. This feature serves as a clinical  
10 reference to help identify the anatomical structures dis-  
11 played on the ultrasound image. It is directly linked to  
12 acquiring the third skills group (image interpretation). As  
13 a result, it is considered valuable for training purposes and  
14 will be included in the simulator.

15 On the other hand, using haptic interfaces was more  
16 challenging for the participants. Firstly, 50% of the  
17 novices found it difficult to grasp and handle them nat-  
18 urally. This could be attributed to the similarity between  
19 the styluses used to control the needle and the probe. Re-  
20 placing them with more realistic 3D-printed shapes of the  
21 probe and needle handles could improve this aspect.

22 Secondly, participants reported difficulty positioning  
23 their arms relative to the haptic devices. This hindered the  
24 smooth movement of the probe, as in real-life scenarios,  
25 clinicians rely on their arm support against the patient's  
26 body to better control their movements. Therefore, it will  
27 be necessary to design physical supports that allow users  
28 to rest their arms while performing the procedure.

29 The force feedback amplitudes provided by the probe  
30 (on the skin surface) and the needle (inside the body)  
31 were perceived as too weak, resulting in faster and less  
32 precise movements compared to real-world. Thus, 52%  
33 of participants were unsatisfied with the haptic feedback  
34 experienced. These scores align with those from other  
35 subjective evaluations of haptic feedback on VR medical  
36 simulators [13, 67, 69]. These studies have highlighted  
37 the challenges of reproducing realistic haptic feedback,  
38 a critical aspect of learning technical skills in medicine  
39 [60, 61, 62, 4], especially hand-eye coordination [70].  
40 Therefore, this aspect must be improved to validate our  
41 system.

42 The first option could be to increase the amplitudes of  
43 the needle's and the probe's friction forces to match real-  
44 world forces better. This requires more precise simula-  
45 tions of the tissue's mechanical properties. Additionally,  
46 using a 6-DoF force feedback arm to control the needle is

47 being considered. The current device does not adequately  
48 constrain rotational movements (lateral forces during ro-  
49 tation) of the needle once inserted into the body. To com-  
50 pensate, we had to restrict translational movements (by  
51 applying translational forces at the insertion point) and al-  
52 low yaw and pitch movements around the insertion point  
53 without force feedback, which reduced the haptic fidelity.

54 Employing a 6-DoF haptic arm would provide rota-  
55 tional forces but significantly increase the simulator's cost  
56 (approximately a 300% increase in the price of the phys-  
57 ical interface, according to our estimations). Nevertheless,  
58 this additional cost is justified by the educational needs of  
59 the system. Alternatively, other approaches could be con-  
60 sidered, such as using pseudo-haptic feedback to compen-  
61 sate for the lack of force feedback. In this case, modifying  
62 the visual behavior of the tool (e.g., reducing its rotation  
63 speed) would create the illusion for the user that the tool's  
64 movements are constrained by the environment, requiring  
65 them to increase their manipulation force to achieve the  
66 desired movement [71]. This passive method could be  
67 combined with a 3-DoF haptic arm to compensate for the  
68 absence of rotational force feedback. Experimental stud-  
69 ies will be necessary to explore the effectiveness of each  
70 method and its impact on learning outcomes.

71 Finally, although involving field experts throughout the  
72 design process did not uncover all the issues, it proved  
73 highly valuable in selecting the system's components.  
74 This initial iteration, with a situated evaluation, relied on  
75 the availability of a functional prototype of the system.  
76 The hands-on experience allowed us to gather feedback  
77 from domain experts, bridging the gap between the real  
78 world and the simulation, with a particular focus on the  
79 fidelity levels of the system components.

80 For instance, describing haptic sensations verbally can  
81 be challenging [13]. By allowing clinicians to test the  
82 simulator, they could compare the force feedback pro-  
83 vided by the system to their real-life experiences and  
84 more easily articulate the relative differences. This ap-  
85 proach was highly enriching and instrumental in identi-  
86 fying fidelity-related issues with the system's interface,  
87 leading to improvements in subsequent iterations.

88 In summary, the results of this study lead to the conclu-  
89 sion that the developed simulator is a promising training  
90 tool for enhancing hand-eye coordination skills in UGRA.  
91 The VE is realistic and reproduces the working environ-  
92 ment of anesthesiologists. The virtual ultrasound inter-

1 face is satisfactory, but improvements are required for the  
2 ultrasound interface and image quality. On the other hand,  
3 issues related to the fidelity of the interface (ergonomics  
4 and haptic feedback) have been identified. Enhancing the  
5 fidelity level of these elements will be necessary before  
6 the system can be validated.

## 7 **8. Conclusions, limitations, and perspectives**

8 This work presents the design of UltRASim, an immer-  
9 sive simulator for UGRA. A user-centered approach was  
10 used with strong involvement from domain experts. For  
11 this, a field study was conducted to build a task model of  
12 UGRA and to identify and characterize the skills required  
13 to perform it. This was then combined with theoretical  
14 concepts on simulator fidelity to guide the system design.  
15 This design approach can be generalized to improve the  
16 design of VR medical simulators.

17 Our approach also involved a user study, allowing us  
18 to validate different system characteristics progressively.  
19 The study investigated the system's face and content va-  
20 lidity, the first two essential steps in validating a simulator.  
21 The results revealed several positive aspects of the sys-  
22 tem design, indicating that it is a promising training tool.  
23 However, certain issues were identified, suggesting areas  
24 for improvement before validating its usability. These ar-  
25 eas include enhancing the fidelity of the haptic rendering,  
26 improving the usability of the physical interface, and in-  
27 tegrating an armrest to support instrument manipulation.  
28 In addition, only simplified representations (cylinders and  
29 cuboids) of anatomical structures were used. The deci-  
30 sion to represent only the main structures (vein, artery,  
31 and nerve) is justified because vascular structures serve as  
32 landmarks to locate target nerves during UGRA. Simula-  
33 tion of other scenarios involving different and more com-  
34 plex anatomical structures (e.g., muscles, bones, pleura)  
35 is considered in the future to enhance the fidelity to the  
36 human body simulation and make the simulator more in-  
37 tricate. Similarly, the simple ultrasound image simulation  
38 with Perlin noise should be improved using more sophis-  
39 ticated noise generation algorithms to achieve images that  
40 better match those displayed by real ultrasound systems.

41 Once these improvements are implemented, further  
42 evaluation studies will be conducted to validate the other  
43 characteristics of the simulator, including its ability to dis-  
44 tinguish between novices and experts (construct validity),

45 its similarity to current training standards (concurrent va-  
46 lidity), and its capacity to transfer learned skills to the real  
47 world (predictive validity). For these studies, objective  
48 performance measurements (e.g., completion time, num-  
49 ber of needle insertions, contacts with structures, quality  
50 of anesthetic injection,..etc.) will be used. In addition,  
51 eye-tracking data could be used to assess how novices ex-  
52 plore visual information on ultrasound images to guide  
53 their movements. Indeed, learning to see the anatomy  
54 through medical imaging systems [72] is an important  
55 skill to acquire, as highlighted in our field study.

56 In addition, while only one anesthesiologist generally  
57 performs UGRA procedures, our field study permitted us  
58 to observe learning situations where experts interact and  
59 collaborate with novices for teaching purposes. This di-  
60 mension could be explored in future iterations of our sys-  
61 tem to introduce the mentorship model into the VR learn-  
62 ing process, where the trainees could benefit from inter-  
63 actions with a more experienced peer. In this context,  
64 we have already conducted an exploratory study to eval-  
65 uate the effect of communication modalities on simple  
66 tool manipulation skills transfer between an expert and  
67 a novice in an immersive environment [73]. Therefore,  
68 we plan to introduce such communication modalities in  
69 our simulator as we think this approach could improve the  
70 learning outcomes, particularly during the early stages.

71 The validation of our system will provide learners with  
72 an alternative and complement to the current training  
73 methods while adhering to the anesthesia societies' rec-  
74 ommendations to enhance practices and ensure patient  
75 safety. The system could also be used in the future to  
76 train other needle insertion-based and ultrasound-guided  
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Table 1: Association of skills and sub-tasks

Sub-tasks	Skills group	Associated skills
2.1.1 Position the probe on the patient	Group 2: image optimization	<ul style="list-style-type: none"> <li>• Learn the importance of the probe pressure</li> </ul>
2.1.2 Orient the probe		<ul style="list-style-type: none"> <li>• Learn the importance of the probe alignment</li> <li>• Learn the importance of the probe rotation</li> <li>• Learn the importance of the probe tilting</li> <li>• Coordinated eye and hand movements</li> </ul>
2.2.1 Identify the anatomical structures	Group 3: image interpretation	<ul style="list-style-type: none"> <li>• Identify nerves</li> <li>• Identify muscles and fascia</li> <li>• Identify vessels, and distinguish between arteries and veins</li> <li>• Identify bone and pleura</li> <li>• Identify common anatomic artifacts (pitfall errors)</li> <li>• Identify vascularity associated with needle path</li> </ul>
2.3.1 Plan the needle trajectory	Group 4: needle insertion and anesthetic injection	<ul style="list-style-type: none"> <li>• Learn to avoid unnecessary tissue trauma</li> </ul>
2.3.2 Insert the needle according to the probe orientation		<ul style="list-style-type: none"> <li>• Learn the in-plane approach, maximizing needle visualization</li> <li>• Learn the out-of-plane approach</li> <li>• Learn the benefits and limits of both approaches</li> </ul>
2.3.3 Control needle progression		<ul style="list-style-type: none"> <li>• Learn to recognize intramuscular needle location</li> <li>• Conduct proper ergonomics</li> <li>• Coordinated eye and hand movements</li> </ul>
2.3.4 Inject the anesthetic		<ul style="list-style-type: none"> <li>• Identify intraneuronal needle location</li> <li>• Learn to recognize correct and incorrect local anesthetic spread</li> </ul>

Table 2: Items of the face validity questionnaire.

<b>Q#</b>	<b>Question text: To what extent did...</b>
Qf1	the VE seem visually realistic to you?
Qf2	the ambient sound seem realistic to you?
Qf3	the visual rendering on the ultrasound screen seem realistic to you?
Qf4	the vein deformation seem realistic to you?
Qf5	the haptic arms handling seem complex to you?
Qf6	the haptic arms handling feel natural to you?
Qf7	the movements of the probe in the VE seem consistent with your own movements?
Qf8	the force feedback during the probe manipulation seem realistic to you?
Qf9	the movements of the needle in the VE seem consistent with your movements?
Qf10	the force feedback during the needle manipulation seem realistic to you?
Qf11	you feel restricted in the needle movements?

Table 3: Items of the content validity questionnaire.

<b>Q#</b>	<b>Question text</b>
Qc1	How promising is this simulator as a training tool?
Qc2	How suitable is this simulator for the development of hand-eye coordination skills?
Qc3	How sufficient did this simulator seem to you to train UGRA skills?
Qc4	How useful was the ultrasound interface to you?
Qc5	How useful was the visual feedback of the spread of the anesthetic to you?
Qc6	How useful did you find the audio feedback?