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Haptic Training Simulators Design Approach

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Abstract. Learning medical gestures requires regular hands-on training to acquire the dexterity needed to perform them without injuring patients. For obvious ethical reasons, this training cannot be carried out directly on the patient. In this context, the use of cadavers has long been the preferred method of training, despite the difficulty of obtaining them and the fact that cadavers deteriorate rapidly. For several years, technologies have led to the development of medical training simulators that combine a numerical simulation (reproducing the organs' behavior during the gesture) with haptic devices (reproducing tactile sensations). As designers of several haptic training simulators, we aim to impart our expertise by detailing in this paper an empirical design methodology for the development of such simulators.

Keywords: Medical Training Simulation · Virtual Reality · Haptics · Soft-body Simulation.

1 Introduction

During their education, medical students have to learn numerous gestures involving the manipulation of surgical tools. The challenge is to acquire the required dexterity, which permits them to reproduce correctly the maneuvers involving the application of a given amount of force to the patient's tissues. However, gesture training performed directly on patients raises medical and ethical issues, as it exposes patients to risks directly related to teaching. For this reason, the use of animals, cadavers and mannequins has become increasingly popular to ensure practical training before application to real patients. Nevertheless, the use of these patient simulation tools cannot cover all possible medical situations, and the physical realism of these simulators diminishes over time. Indeed, tissues remain permanently deformed after initial use, and physical properties change as the body decomposes, altering blood supply or tissue structure.

In this context, the use of training systems offering Computer-Based-Simulation (CBS) [40] can provide an answer to these training issues as their use enables coverage of a wider range of medical situations. Nonetheless, the effectiveness

of such training tools thus depends on the pedagogical validity of the situations proposed and on the appropriate realism of the simulation, with the apprentice immersed in an engaging scenario. The first CBS designed for this purpose are categorized as Virtual Reality Training Simulators (VRTS). They have become increasingly prevalent due to their provision of objective feedback and diverse case scenarios [10]. Nevertheless, they frequently lack realistic haptic feedback, a crucial element in enhancing the medical skills of the trainee [55]. In this context, the use of Virtual Reality (VR) with haptic devices has emerged as a growing option in recent years. These Haptic Training Simulators (HTS) [41] integrate a numerical simulation replicating the behavior of organs with a haptic device reproducing kinesthetic sensations. This combination allows learners to perceive the consequences of a medical gesture. Furthermore, they facilitate training with force feedback, aiding trainees in immersing themselves in diverse situations, as highlighted by research such as [50,30,57].

The challenges of these types of medical simulators are: to ensure patient-friendly learning of medical procedures as part of initial and continuing medical training; to accelerate the learning process by multiplying and targeting the situations encountered; to improve knowledge of the procedure and associated reasoning; in the medium term, to develop new medical procedures and associated assessment methods; in the longer term, to offer tools for pre-operative planning and training in high-risk "patient-specific" operations, i.e. medical simulators directly based on a patient's medical data.

In this paper, we focus on training tools based on a numerical simulation combined with a haptic device. We introduce a proposal for a complete process of design of such simulators for hands-on training in medical and surgical procedures. Yet, we do not include the educational dimension which deals with designing training scenarios and objective assessment, for the sake of clarity. In section 2, we present a brief state-of-the-art on medical training simulators. Section 3 introduces the aforementioned design approach, and section 4 is a discussion about the evolution of these simulators toward patient-specific ones.

2 State of the Art

As far as we know, the latest general review (larger than the medical scope) about training simulation was proposed in 2020 in [41]. Since, some more focused reviews are available, such as [30] for tissue examination, [15] on needle insertion, [35] in anesthesia, or more recently [54] in transfusion medicine, for instance. In 2007, Gardner [24] proposed a state-of-the-art report on the use of simulators in obstetrics and gynecology, accompanied by a classification: anatomical simulators, instrumented anatomical simulators, and virtual-reality-based simulators. We propose updating and extending this classification to any contemporary medical training simulators.

Anatomical Simulators. As they are the least expensive at the purchase time, the most widely used simulators in medicine are anatomical ones that reproduce

anatomical landmarks. For example, in obstetric gynecology, the simulator proposed in 1951 by Graves [28] consists of a woman's dummy on a scale of one, with three levels of gestation, a placenta and a fetal dummy that can be positioned in different ways in the abdomen. The most simple ones are sight-only: they cannot be used to practice any gesture (needle insertion, suturing, etc.) which limits the didactic dimension. More evolved ones feature parts that can reproduce *passive haptic feedback* (when inserting a needle, for instance), based on materials presenting similar mechanical properties to tissues of interest. Yet, these parts progressively wear out, which can be costly in the long term. For instance, Clifton *et al.* [12] introduced a 3D-printed open-access spine simulator and Robberecht *et al.* [53] a ceramic root canal simulator for endodontic training. It has been demonstrated that 3D printed models are realistic enough and cost-effective to help trainees in the first phases of some other specific medical training (Otolaryngology [63], and Pediatrics [44], for instance).

Instrumented Anatomical Simulators. Instrumented anatomical simulators offer *active haptic feedback* in addition to the features of anatomical simulators. This feedback is obtained through actuators that are controlled (by the trainer, for instance) to render realistic force interactions between the manikin and the tools or the hand of the trainee. We can cite, as examples in gynecology, the following ones [38,17,60,52,2]. Among them, the Noelle simulator from the Gaudard company [25] represents a complete product in the "learning dummy" philosophy, with simulations designed to teach the reflexes required in different typical situations. For needle insertion, let us cite [18].

Virtual Reality (VR) Simulators. With the advent of new technologies, a more recent class of simulators concerns VR-based simulators. A numerical simulation reproduces interactions between medical tools and organs. The simulation permits taking into account a patient's morphology in comparison to a plastic dummy. In gynecology, these simulators enable the trainer to visualize the descent of the fetus into the pelvic canal [8,26,36,23,6]. The use of VR glasses [6] can enhance the learner's immersion in the virtual world. Letterie [42] highlighted in 2002 the benefits of Virtual Reality for training in obstetrics and gynecology. Augmented Reality simulators also enter this category, such as [61] for epidural need insertion, [49] for rehabilitation, or [45] for horticultural therapy.

Haptic Training Simulators (HTS). As anatomical simulators, whether instrumented or not, are based on plastic mannequins, they can not simulate complex tissue interactions and therefore do not offer realistic high-fidelity sensory rendering when medical instruments are in mechanical interaction with tissues. Yet, gesture precision depends on the reaction of tissues and anatomical structures that evolve during the gesture. Also, these simulators cannot reproduce a variety of clinical cases without multiplying the samples, and they wear out in time, which requires purchasing new parts that can be costly in the long term.

In comparison, haptic training simulators provide kinesthetic feedback using a (off-the-shelf or specific, see [59]) haptic device. It is, in general, a robotic arm that is controlled to furnish the end-effector position to the simulation software and to generate a force that resists the motions of the user, computed in real-time by the simulation software. Haptic feedback can also be provided by using complementary tactile devices [50,22]. Nonetheless, this paper focuses on kinesthetic feedback. For example, Buttin *et al.* [11] proposed in 2013 a child-birth simulator to learn extraction gestures using forceps. The descent of the fetus was simulated according to uterine contraction and expulsion forces. The computed head's position was used to pilot a pneumatic device corresponding to the haptic part of the simulator [32] comprising a maternal abdomen and a plastic fetus. Concerning needle insertion haptic training (a very common gesture), Correa *et al.* provided a state-of-the-art in 2019 [13]. Since, Alamilla *et al.* introduced such a simulator in a rheumatology context [1]. It combines a numerical simulation, providing an ultrasound view of tissues during the gesture [7], with two haptic devices (one for the probe and one for the needle). Some other recent haptic training applications cover prostate biopsy procedures [21], intraoperative ultrasound [3], or tissue examination [30].

HTS have been demonstrated as efficient, particularly in laparoscopic surgical training [29,51]. Moreover, Sue *et al.* [62] performed a relative evaluation of HTS *vs.* VR ones. Correa *et al.* [13] also concluded that simulators coupling virtual reality and haptic feedback are the most promising ones. Nonetheless, the design of such realistic simulators remains challenging.

3 From Medical Need to Simulator Design

Designing a simulator to train on a medical procedure involves several steps, from identifying the medical need to validating the didactic capacity of the simulator. Moreover, it requires a multidisciplinary approach: in didactics, to produce simulators with a significant contribution to learning by identifying what to simulate and setting up relevant learning scenarios [65]; in computer science and mechanics, to create interactive simulations with a degree of precision appropriate for learning; in robotics, to design a haptic interface adapted to the targeted gestures and restoring the sensations usually felt by physicians during these gestures; and finally clinical, to analyze and validate the various parts of the simulator [20]. In the following, we focus on the development of the two technical parts that have to be combined to design a haptic training simulator.

Firstly, the designer has to identify the operation to simulate (Section 3.1 and Fig. 2). This requires getting scientific data to reproduce the phenomena as realistically as necessary for training purposes. Then, one has to design the *numerical part* (Section 3.2) which simulates the behavior of organs interacting with each other and with medical instruments. It can provide a visual rendering of reality or on the contrary, it may show to the trainee (and also sometimes to the trainer) areas that are usually hidden (Trainee HMI in Fig. 1). Moreover, this numerical part computes the force information required by the haptic device.

Section 3.3 describes the design of the *haptic part* of an HTS (Fig. 1) that enables the trainee to manipulate the usual medical instrument(s) and reproduces the kinesthetic sensations felt during the procedure. The *coupling of the two parts* is detailed in Section 3.4. The design process generally requires a parallel development between the numerical and the haptic parts. As, in general, precise model parameters are not available in the scientific literature, a test-and-trial process is necessary to tune the simulator based on expert user feedback. This design process ends with the description of the validation steps (Section 3.5).

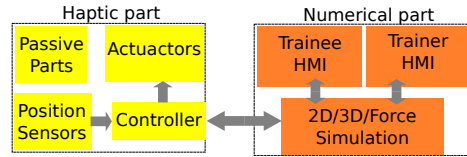


Fig. 1. Generic architecture of a Haptic Training Simulator (HTS).

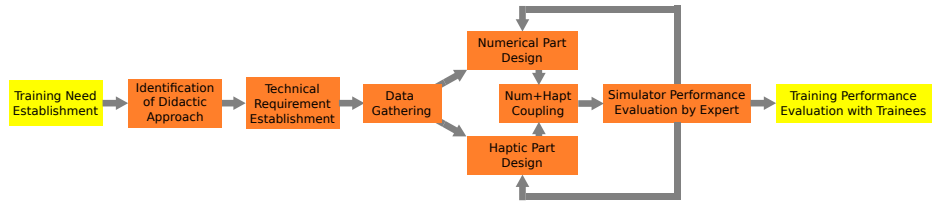


Fig. 2. Haptic Training Simulator Design Process.

3.1 Common Identifications

To reproduce tissue behavior at a sufficient and necessary level of realism previously identified during the didactic study (*Identification of Didactic Approach* in Fig. 2), the designer of an HTS must identify the relevant models of the different components of the simulator: the specific trajectories and forces provided by the user on the real instruments and the specific interactions (such as tissues cutting, needle insertion, tissues deformation, etc.) which have to be rendered in the haptic and virtual components.

However, it is difficult to get direct real data to feed the numerical simulation models when it concerns medical gestures. One first approach consists of browsing the **scientific and medical literature** for data (forces, trajectories, (bio)mechanical behaviors). These data are often rare or not usable for the haptic part design or can provide different values for soft tissues as it is still challenging to characterize them. Therefore, it may be necessary to equip

an expert during medical procedures with position/orientation sensors to record the trajectories, and force sensors inserted between their hand and the tools or between the tools and the environment. This process can include expert ones that will be used as reference in a first approach, and novice ones that can deviate much from the latter. Also, the level of precision of the simulation must be determined to obtain realistic behaviors as fast as necessary to update the visual and haptic renderings. Therefore, model simplifications must be applied to reduce computing time.

3.2 Designing the VR Part

The complexity of medical simulation makes real-time execution a challenge. It depends on the discretization of the objects into a greater or lesser number of elements or nodes on which the simulation is performed, the physical model used to represent the mechanical behavior of the object with a more or less complex constitutive law and the numerical methods employed during the simulation. Therefore, one has to play with these parameters to adjust the compromise between computation time and accuracy.

From Medical Imaging to Meshes. Various tools are now available to transform through segmentation medical images (CT Scan, MRI) into a mesh representing the objects, often first of all in surface mesh, which can then be used to create a volume mesh of the object. Some manual processing is still required to ensure the quality of the elements created. One can then simplify these meshes to reduce their number of elements while preserving their anatomical features to not induce important errors in the simulation.

Real-Time Simulation. In terms of the physical models employed, two approaches predominate in the medical context: a continuous approach aims to solve the equations of mechanics, and a discrete approach, based on a non-continuous representation of the material, aims to calculate the motion of interacting particles. For instance, in training on the use of forceps for fetal extraction in a childbirth simulator, the difficulty is to simulate, in interactive time, the deformations undergone by the fetal head during delivery. These deformations are the result of intra-uterine pressures exerted on the skull and the potential use of forceps to extract the fetus. From a mechanical point of view, the fetal head can be seen as an incompressible deformable object with a fine structure. For this reason, the approach adopted by [4] was to use a surface model, as it allows objects to be modeled with a smaller number of degrees of freedom than a volume model. The challenge then lies in ensuring that the surface model reproduces the complex behavior of a volumetric object, while guaranteeing the conservation of its volume despite the deformations undergone during simulation. In this context, Baillet proposed a model based on shell finite elements, which are surface finite elements derived from thin plate theory. This modeling is combined with

a volume preservation method that ensures volume conservation during simulation, and an original parallelization approach that reduces numerical simulation computation time. As discrete models, the mass-spring system has been widely used in computer graphics for its ease of implementation and speed of calculation. However, the behavior reproduced by the system is topology-dependent, i.e. it depends greatly on the configuration of the connections established between the masses by the springs. Moreover, one difficulty lies in the formulation of the spring stiffness to incorporate the mechanical properties of the material (notably Young's modulus and Poisson's ratio). Hopefully, many papers manage to improve this aspect [16,47,39,27]. Thanks to these advances, Ballit [5] et al. proposed a childbirth simulator integrating a simulation based on the Hyperelastic Mass-Spring Model (HyperMSM). Nonetheless, in the medical field, the Finite Element Model is often preferred for its accuracy. To reduce computing time, a wide range of research improved its computation time thanks to parallelization on GPU or simplifications [19,67]. Within this framework, the constitutive law plays an important role in the simulation's complexity. As the soft tissues have non-linear behaviors, the hyperelastic models (Neo-Hooke, Mooney-Rivlin, Yeoh, or St Venant Kirchhoff laws) are generally preferred in a medical simulator as they permit obtaining adequate precision while being simple.

Appropriate Visualization. Depending on the simulator developed, the simulated objects' visualization can vary. For example, the training simulator proposed by HelpMeSee [9] offers a realistic view of the eyes comparable to that seen during cataract surgery. In rheumatology, practitioners guide their gestures by observing on-screen the restitution of the ultrasound probe placed on the patient. To be consistent to this practice, the needle insertion simulator proposed by Barnouin et al. [7,1] offers a real-time ultrasound rendering showing tissue deformation during needle insertion depending on the probe's orientation.

Simulation Validation. The validation process is complex. For instance, how to validate a childbirth simulation without a dynamic MRI or the possibility of putting sensors on a fetal head during its extraction thanks to forceps? A first approach is to rely on medical knowledge of behavior. And the ideal would be to rely on other simulations established as "gold standards" to be achieved. These simulations are based on the most accurate modeling possible of the target organs, and a robust resolution method. But these standards necessarily include precision errors, as they are themselves simulations based on medical images produced at a certain resolution, and they are also based on measurements taken on soft tissues, with an error due to experimentation, and so on. Therefore, it is necessary to quantify the error produced throughout the processing chain, to provide the final error of the simulation and make compromises accordingly.

3.3 Designing the Haptic part

The haptic part has the responsibility to render a kinesthetic feedback of the simulated gesture. In some rare case, it works in admittance mode: the user ex-

erts forces on the haptic device that is controls its position. This was notably the case with the BirthSim [32,31,33] forceps simulator. However, most of the commercial haptic devices work in impedance mode: the trainee positions the end-effector of the haptic device and the latter exerts forces on the trainee’s hand to render interaction forces computed by the numerical part. The haptic part features sensors to detect the user inputs (position in impedance mode, interaction forces in admittance mode), the actuators to provide haptic feedback (in general, electric motors, but it can also be pneumatic actuators as in [64]) and a controller to perform the force/motion control synchronized with the numerical part (see Fig. 1). In some cases, they also feature passive parts that are static objects that help trainees get immersed into the simulation (a crane for ventricular puncture, a back for epidural anesthesia, ...). These parts are also refereed as tangible simulation objects as in [14].

Dimensioning and Haptic Device Selection. Considering the preliminary identified gestures and phenomena to render that require generating force feedback, one needs to determine the required mechanical characteristics of the haptic device: the number of (actuated or free) Degrees of Freedom (DOFF), its workspace, and the maximum available force. The range of stiffness is also an important parameter: from fat to bones, the range is large and is an important variable for the haptic device dimensioning. In a proof-of-concept approach, a general-purpose haptic device is preferred. In general, they are over-sized but their use then helps refine the technical requirements and design a specific optimized haptic device in a second phase. Commercial haptic devices such as Delta.6 (Force Dimension), Virtuose (Haption), Touch (Geomagic), Falcon (Novint Technologies Inc.), etc., may be used according to the requirements. In this case, to provide a better immersion, the trainees should feel like they are handling the real tool. Using general purpose haptic devices, it is sometimes possible to remove the handle and adapt a fake tool, like an epidural needle in [58] (see Fig. 3 that also illustrates some specific designed haptic device with the pneumatic cylinder emulating a syringe).

Yet, in some cases, no existing haptic device fitting all the requirements is available. For instance, Khedar *et al.* [36] concluded in 2004 that using a commercial haptic device for a childbirth simulator is not adequate, and that it is clearly necessary to develop a dedicated interface. A sample of specifically designed haptic device can be found in [34] concerning microsurgery.

Haptic Behavior Rendering. Once the haptic device chosen or designed, one has to determine which algorithm is adequate and its parameters. Concerning the execution of these algorithms, in general, each haptic device is associated with an SDK to program the haptic behavior (for instance, for the Touch and Phantom Premium (Geomagic), OpenHaptics by 3D Systems). These software packages permit to render standard haptic behaviors (hard or soft contact, friction, etc.). One has then to connect these functions to the numerical part to render force feedback, without having to program the low-level automatic con-

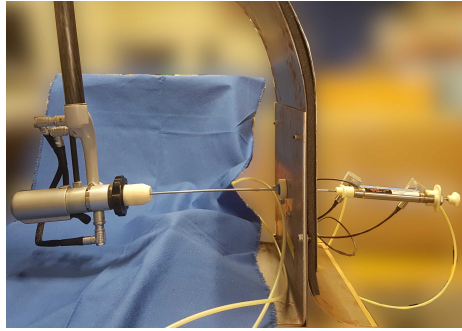


Fig. 3. Adapting a fake needle to a general-purpose haptic device (Haption Virtuose 6D). The coupled Loss-of-Resistance syringe is emulated by a pneumatic cylinder.

trol of the actuators of the haptic device. For specific devices, automatic control is necessary to render force, position and/or stiffness control, such as in [57].

Transient Haptic Rendering. The force feedback provided by the haptic device is rarely static as human tissues are composed of soft materials, which usually are anisotropic and inhomogeneous, and exhibit highly non-linear viscoelastic behaviors when they are subject to high strains [46]. In some cases, like in needle insertion, there exists models indicating the behavior of the needle-tissue interaction which permit to determine the evolution of the force feedback in time and in the space [15]. Providing a realistic force feedback requires refining the transitions between different haptic behavior areas, more particularly when they chain themselves in time or in the space. For instance, still in the context of epidural needle insertion, the realistic simulation of the crossing of seven layers of tissues required to provide a model of their stacking. Some *pseudo-tactile sensations* can also be necessary to be reproduced by the haptic device such as vibrations [58].

3.4 Coupling the VR+Haptics

The challenge of developing an HTS is to combine the numerical part embedding the simulation that reproduces realistic organ behavior in interactive time, with a haptic device providing kinesthetic perception, while ensuring the whole's stability. A first difficulty is linked to the necessary refresh rate of haptic devices (minimum 1 kHz) to enable feeling hard contacts, while medical simulations struggle to run as fast. An interface between these two-pace software programs is then necessary. A second difficulty is linked to the sampled nature of haptic control in the presence of hard contacts. At the frontier of the material, the virtual position of the tool oscillates between two positions inside and outside, which generates undesired vibrations. The coupling between haptic interfaces and numerical simulations is then usually performed using a *virtual elastic coupling*, named method of "god object" introduced by Salisbury *et al.* in [56]. This

method has been enhanced later in [66] for low-force applications and in [48] for rigid objects.

3.5 Validating the Simulator

The scientific barrier inherent in medical simulator concerns the validation phase: firstly, each part of the simulator must be approved for its behavior; secondly, its suitability for medical training must also be confirmed. Thus, scientific validation of the learning is essential for the use of a simulator in the care of healthcare students and for the further training of healthcare professionals. To this end, Donald Kirkpatrick's model [37] has been for example recommended by the French National Authority for Health. The validation is decomposed in four steps: (1) *reactions* - to focus on learner satisfaction after a session on the simulator about the objectives, content, and equipment; (2) *knowledge/skills* - to check the objectives' achievement in terms of knowledge and skills; (3) *behaviors* - to analyze the behavioral changes in the professional practice due to acquired skills and abilities; (4) *results* - to look at the simulation impact on patient management. This assessment can be based on questionnaires.

4 Discussion

The process depicted here is elaborated on the experience of around ten years of designing various medical HTS. This empirical process is a simple testimony of what has worked, to help in the design of new ones and converge more rapidly with tested solutions. As aforementioned, it is difficult to evaluate the quality of the numerical simulation and the forces felt using haptic devices when it concerns the simulation of a medical gesture. Without objective data available in the scientific literature, one has to use subjective validation provided by a group of experts through tests and trial attempts or acquire medical data. Yet, acquiring data on patients is a very complex task as it necessitates conforming to ethical standards and must not disturb the staff during a medical gesture. Moreover, it is mandatory to test the didactic efficiency of the simulator on a sufficiently large panel of trainees, before its real use. Hence, the skills acquired on simulators must be fully transferable to a real patient.

The interest of a formalized design procedure is to progressively enhance haptic simulations. Emphasizing the difficulties and the critical parameters limits the risk of delays and unplanned costs. This proposal has been thought to be as generic as possible. As it is a first (as far as we know) attempt to model the building of such simulators, enhancement ought to be brought in. For instance, the Augmented Reality (AR), tactile, and acoustic feedback dimensions have not been taken into account. Also, the interactions in dual-user simulations [43] have not been evoked in this paper.

Patients are unique. So, training simulators can only train in generic cases. One challenge of developing such HTS for learning medical gestures concerns the creation of patient-specific simulations. Embedding parameters to enlarge

the set of available situations, validated by experts, brings much interest to this kind of hands-on training. Furthermore, if the simulator can tune itself starting from new medical images (MRI, ultrasound) in a human-acceptable time (a few minutes ?), it opens the way to patient-specific simulation and the opportunity to train oneself on the simulator before any operation. Such simulators will enable training, for example, in the resection of a hard-to-reach tumor, to check the feasibility of a vaginal delivery, or to measure the damage to the tissues and ligaments of a parturient woman’s pelvic floor following a natural delivery.

The scientific hurdles to overcome are then how to achieve interactive simulation time with models generated on the fly from raw medical image data. Today, using patient-specific data (medical images, tissue elasticity parameters, volume of breath measured by a spirometer, etc.), one has to rapidly build a geometric model of the organs involved in the medical procedure, and to develop a physical model integrating the measured mechanical parameters in order to produce an accurate simulation of the targeted medical procedure for the simulator’s numerical part. The accuracy of organ behavior thus becomes a major constraint, which could be slightly relaxed for learning simulators. Making it automatic requires to efficiently segment the images, recognize the organs, and apply corresponding biomechanical models. Nonetheless, a fixed image does not bring sufficient information to guess the model parameters that fit the patient tissues. Ideally, some dynamic imaging input would be better. Nonetheless, this requires to evaluate the ability of the simulator to adapt itself to cases that are unknown in advance. It will require a design based on a training set of data and a validation on a test population as for AI validations, knowing that the dimension of each should be at the scale of thousands cases.

5 Conclusion

The development of medical training simulators based on virtual reality and haptic techniques aims to improve medical hands-on training. The objective is to enable trainees to acquire the dexterity required for medical gestures by following several exercises in line with the learning process without any risk to the patient. As evoked in this paper, their development requires the designing and programming of (sometimes custom) haptic devices to reproduce kinesthetic sensations and enable interaction with a numerical simulation reproducing the behavior of organs during medical procedures. Even if works bring generic approaches such as needle-insertion haptic simulation, it remains difficult to transpose the results obtained with one simulator to another one for different medical procedures. This is why this paper introduced an empirical design process detailing the haptic and numerical parts, and their coupling, based on more than one decade of design of such simulators. Currently, haptic training simulation evolution leads to mixed simulation integrating tangible objects to manipulate or palpate and RV+haptics. Next generation training simulators should enable patient-specific training, based on specific patient medical imaging inputs.

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