Virtual lumbar puncture simulators: where are we today?

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***Abstract*—The lumbar puncture is an important procedure used in different specialties in medicine, such as neurology and anesthesiology. This procedure is considered complex, and the medical students believe they have not enough experience and confidence to perform it. That is the reason why some researchers are interested in proposing to create solutions to provide a better training of this procedure. This review aims to present a comparison between 10 virtual lumbar puncture simulators developed since 2000, where nine of them use a haptic device to represent a realistic procedure. In addition, the physical and virtual components are discussed, including the haptic device, the haptic algorithm, the virtual environment and the evaluations of the simulators. The contribution of this review is to recognize the limitations and strengths to identify some optimal requirements for the design, development, or selection of the software/hardware for the next generation of virtual lumbar puncture simulators.**

I. Introduction

The lumbar puncture (LP) is an invasive procedure where the physician inserts a thin needle into in the lumbar region, passing through different tissues, piercing the dura and accessing to the subarachnoid space [1]. This procedure is used for treatment, such as drug delivery or cerebrospinal fluid (CSF) removal to decrease intracranial pressure; and for diagnosis through the CSF sampling [1], [2].

LP is considered as a complex and difficult procedure, whose success is related to the knowledge of the contraindications, the anatomy of the zone, the steps of the procedure, the technique and the skills of the physician [3], it means, the success of the procedure is correlated with the physician experience. Following an LP, the patient can experience some adverse events, such as post procedural headache, hemorrhage, infections, nerve injury, CSF leak, cerebral herniation, backache, hematoma, implantation of epidermoid tumor, radicular pain or seizures [4], [3].

The LP procedure consists of different steps that involved technical and non-technical skills. In general it is described as the insertion of the needle in an intervertebral space between the L2 and L5 vertebra. The main characteristic regarding this procedure is that the biomechanical behavior of the tissues helped the physician to distinguish the layers when the needle pass trough. These layers are the skin, subcutaneous fat, supraspinous and interspinous ligaments, ligamentum flavum, epidural space, and dura mater [5]. The biomechanical behavior can be described as a “pop” or loss of resistance when the needle pierces the dura mater and the needle is inside of the subarachnoid space, where the CSF is [6].

Because this procedure in general has a negative perception from the population, the physician has the task of explaining LP and showing a positive and trusting attitude towards it, however some medical students perceived the LP as an important but complicated procedure, with not enough experience and confidence [7].

Medical students can learn the LP with different techniques, and the lack of experience can generate error in the detection of each layer causing a wrong LP [5]. Some of the students learn this procedure through observation sessions as in the apprenticeship method, where the student with the guide of an expert, performs the LP directly on a patient in a clinical environment [6]. This method has some disadvantages because the student is under stress for the possibility of make a mistake and cause pain or injury to the patient [6].

Other technique is the use of mannequins or training models built with plastic or rubber, without mechanical or electronic parts. They are portable, easy to use and to set up, with anatomical landmarks for palpation, with them the students can repeat the procedure and can feel the loss of resistance of some tissues, however, they present some limitations such as the limited number of uses before replacement of the fake tissues (consumables), limitation in mimicking the exact biomechanical behavior of tissues, the assessment of the training and the limitation represented by pathological and anatomical variances of the lumbar anatomy [5], [6], [8].

Virtual simulators have been developed in order to eliminate these limitations using technologies such as haptic devices and computer controls or virtual reality (VR) [8]. In general, the use of this technology allows the use of medical images for more precise anatomical models, and also for the representation of different anatomies or some physiological differences.

VR can be defined as the use of computational models that allows the user interaction with artificial environments and objects, it simulates the reality through interactive devices, and sends or receives information from the virtual environment (VE). The virtual reality is classified according to the level of immersion or presence [9], [10]:

- Desktop VR: It is not immersive, but it is the most common and cheapest because it uses a monitor as the visualization system, it can also include a haptic device.
- Semi-immersive VR: It transmits to the user a sense of immersion within the VE on a visualization system larger than the monitor.
- Fully immersed VR: The user is fully immersed in the VE and isolated from the real world, this is achieved through devices such as the head mounted display (HMD).

On the other hand, a haptic device is an electromechanical device that enables communication between the user and computers through the sensation of object manipulation. These devices provide haptic or tactile feedback in the form of force, vibration or with a propioceptive response, following the interaction with a virtual object [11].

It is worth mentioning that in the literature there are review articles that analyze virtual medical simulators in a general way like in [12], or for specific areas, like in [8] where epidural simulators based on mannequins or virtual are presented. However, this review will focus exclusively on those simulators that were developed to simulate LP.

The contribution of this review is to identify the requirements that a virtual LP simulator should cover to improve the skills and training of this procedure. Moreover, this paper also provides a comparison and analysis for researchers interested in developing a LP simulator, showing the necessary characteristics for the design of the virtual environment, and the selection or design of the haptic device. In addition, 10 simulators developed since 2000 are mentioned, each simulator includes its VE description, the technologies implemented (haptic device and visualization system), the haptic algorithm, and if the simulators were tested for usability or they were involved in a user experiment.

For this review a bibliographic search on the electronic Google Scholar database using the date intervals 2000 to 2022 was performed with the next keywords “Lumbar puncture (LP) simulator, virtual simulator, haptic simulator”, where only simulators with a virtual environment that represents a LP were selected. In addition, the papers must describe in general terms the features of this simulator, such as the VE and what devices were implemented for allowing the user interaction with the simulator. Narrative data were extracted from each paper using the categories presented in Table I of Section IV. It is worth mentioning that papers developed for other puncture procedures were excluded from this review, for instance, as the epidural anesthesia or analgesia.

The reminder of this paper is organized as follows, Section II presents the non-commercial LP simulators in chronological order. Section III presents the commercial LP simulator. Section IV analyzes and discusses the advantages and disadvantages of the simulators. And, Section V shows the conclusions.

II. Non-commercial LP simulators

Gorman et al. [13] describe the development of an LP simulator, the VE includes 3D models of the spine from L1 to the sacrum, the spinal canal area and a virtual needle. The simulation includes six tissues layers: skin, dermis or subcutaneous tissue, muscles, ligamentum flavum and dura. This system consists of a Phantom 1.5 desktop (from Sensable Technologies) as the haptic device, a mannequin, and a monitor. Authors attached a needle in the final effector of the haptic device, in order to improve the interaction between the user and the simulator (see Fig. 1). The haptic device provided force feedback according to the virtual tissue penetrated by the virtual needle. This force was calculated according to the angle, deep of the needle and penetrated tissue. Each tissue was modeled as a haptic box, allowing the user to feel the friction of the surface, the force of the puncture and the damping effect. The values of each haptic box can be modified by the user, allowing to feel when the needle pass through the skin or collides with a bone. This simulator provides the possibility to see through the tissues and has the option to record the training and play it more times. The authors wanted to add a system to measure and track performance, but there is no information on whether it was done or not. The evaluation of this simulator is not presented in the paper.

In 2009, Färber et al. [6] developed a VR simulator with a VE with 2D and 3D scenes. The scenes (see Fig. 2) showed a virtual needle and the surfaces of anatomical structures with different colors and opacities for each organ and the anatomic landmarks can be identified by the trainee, additionally the VE shows annotations related to the anatomy. The scene was obtained from computed tomography data. In general, the scene could be rotated, panned, and zoomed with the mouse. This simulator integrates the 3DoF (degree of freedom) Sensable Phantom Premium 1.5 as haptic device, which gives force feedback according to a haptic algorithm. For the force

Fig. 1. Haptic device, mannequin, needle and virtual environment of the simulator developed in [13].

feedback authors integrated a proxy-based haptic rendering, that consists in a virtual spring damper that connects the end effector of the haptic device and a virtual proxy; and a proxy-based haptic volume rendering, in general the proxy moves perpendicularly to the direction of the image gradient vector, it means that the force can be calculated according to the information of density of the image. In addition, the simulator has three modes according to the experience of the user (beginner, advanced and professional), and provides an evaluation module that records the movement of the needle, and its path is compared with an optimal path, also the piercing of bones or structures at risk are evaluated in a score from 0 to 100. After the evaluation, the system could give feedback related to user performance and advised about how to improve the procedure. On the other hand, the system had some limitations such as the haptic device used cannot provide real force feedback for the collision with bones, also the intuitiveness of the system was limited because they use a monitor causing that the user is not immersed, and the end-effector of the haptic device did not represent a needle. 42 participants evaluated the system in two groups, the control and the training group. Both groups followed the same study protocol, where they studied didactic material, then an introduction to the LP was given to then start a tutorial for the use of the haptic device, then the training group trained with the LP simulator and the control group practiced other procedure; the next day both of them trained with the LP simulator. The participants belonging to the training group obtained better results and a higher success rate than the other group.

Fig. 2. Virtual lumbar puncture simulator with stereographic visualization [6].

Jiang et al. [14] presented another solution for the LP training with remote haptic collaboration (see Fig. 3). In this paper the VE is not described, but the system worked with two haptic devices for a collaboration between a medical teacher and a student, both manipulated a local Phantom Desktop (haptic device), i. e. when the teacher manipulates his Phantom the student receives the information as force feedback with the second haptic device by means of a local network. This haptic device has 6DoF and provides force feedback in 3DoF, this feedback is calculated according to the tissue penetrated. For the haptic algorithm, the system used the mass spring system for the interaction between the needle and viscoelastic tissues, also used a friction model proposed by Karnopp and the clamping force. The user experience of this simulator was evaluated by 20 experienced physicians (10 pairs), at the end all of them succesfully perform the LP and felt the haptic force feedback in the ligament.

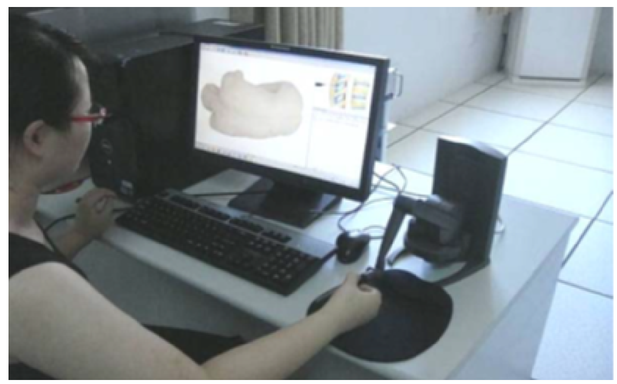

Fig. 3. Virtual environment with remote haptic collaboration [14].

In [15], Day presented an LP trainer that consisted of a haptic device and a virtual environment for training simulation. For the VE, authors used the Unity3D game engine for the creation of a model created with computed tomography data, and consisted of the spine, pelvis, and torso (See Fig. 4). This simulator used the Novint Falcon with 3DoF (X, Y, Z directions) that provides force feedback proportional to the force used by the surgeon during the insertion of a needle. Authors highlighted the need of validate this simulator for training, however this evaluation is not mentioned.

In [16] Wang et al. developed a Surgical Training System that includes the LP and other three more punctures (thoracentesis, bone marrow puncture, abdominal paracentesis). Each type of puncture had its own models for the surgical instruments (See Fig. 5), and a specific human model with organs and tissue related to the type of puncture. The system considers several models like clinician and nurses, and several surgical scenes were designed. These scenes included operating rooms and a patient on the table, chair, or bed. The surgical trainer was developed in the Unity3D game engine with a server program developed in PHP, and an HMD was implemented as visualization tool for the surgery scene. Authors did not mention the haptic device used by the system, but they mentioned the use of the finite element method and

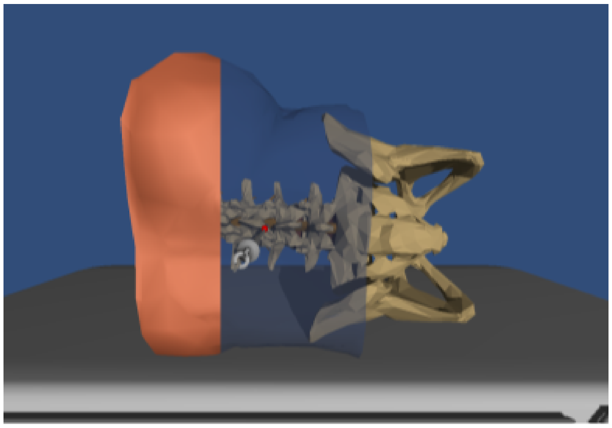

Fig. 4. Virtual environment described in [15].

a mass spring system for soft tissue modeling. The system records the number of completed procedures, the competition rate, average finished time, and the procedures. No evaluation was carried out for this simulator.

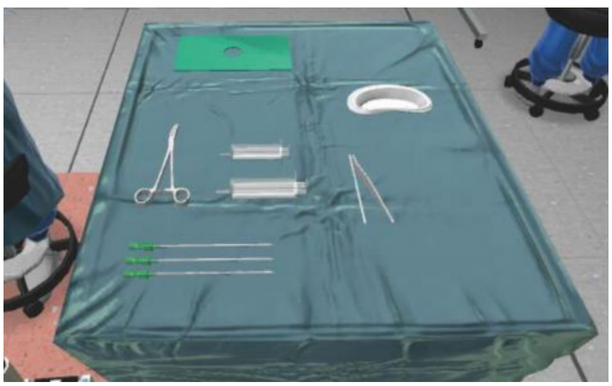

Fig. 5. Virtual environment with 3D surgical tools [16].

In [17] José et al. developed a bi-manual haptic simulator for LP and palpation was presented. The system consists of two haptic devices and a VE which consists of a virtual needle, a virtual hand and a virtual body with the spinal column from L1 to sacrum (see Fig. 6). One of the haptic devices was used for palpation implementing a Novint Falcon, this device controlled a 3D model of a hand; the other one was a Phantom used to control the movements of a 3D virtual needle. These devices were connected to a computer with a visual display, where the user could see the virtual environment that display a hand, a needle, and a human body model. For the palpation, authors implemented a lateral haptic model consisting of lateral surface force feedback, whose forces acted in a normal direction of the thumb; on the other hand for the puncture, they used a layered haptic model, where each layer is modeled as a haptic box, and the forces were calculated according to the characteristics of the material of the layer, the needle position, and orientation. This simulator was not been evaluated.

In 2018 [18] a virtual fluoroscopy-guided lumbar puncture module was developed using the ImmersiveTouch platform (see Fig. 7). The VE consists of a 3D lower torso model (lower spine, ligamentum flavum, posterior paraspinal muscle groups, subcutaneous fat and skin) created from a segmentation of anonymized CT datasets, and a virtual spinal needle. This system integrates a haptic device and a hand tracking tool that enable interaction between the user and the module, also there are some foot pedals that control the simulation of fluoroscopic images, and with a button they can rotate the image and obtain oblique images. The authors did not mention in what consists the haptic algorithm, but they provide haptic force feedback so the users can feel the resistance of the skin, the “pop” when they pierced it, when the dura is penetrated and the impenetrability bones. This module was evaluated in a pilot study with five radiology trainers and a radiology nurse practitioner, the participants use the simulator for 30 minutes, with at least one LP with fluoroscopy, then they were asked to answer a survey, where the participants mentioned that the module replicated in a realistic way the anatomy and the fluoroscopy, five participants mentioned that also the anatomy was replicated with the haptic feedback, and finally the training overall obtained a score of 4.3 in a range of 3 to 5.

Fig. 6. Bi-manual haptic virtual lumbar puncture simulator [17].

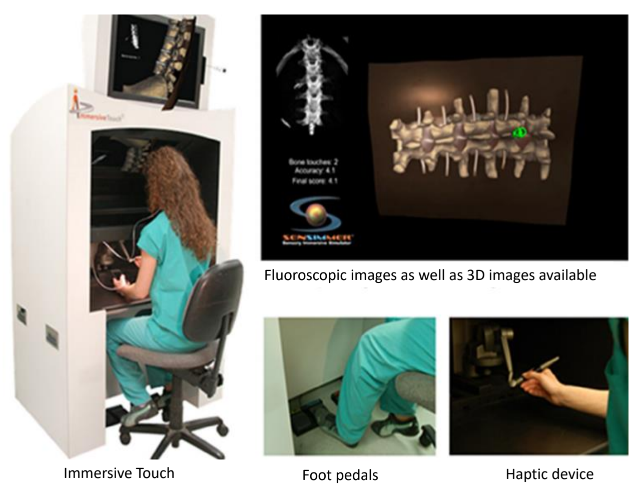

Fig. 7. Lumbar puncture module with fluoroscopy of Immersive Touch [18].

In 2020 Mirbagheri et al. [5] developed the LP Sim, which consists of a software with a force module and a VE developed in Unity. For the VE authors created a geometrical 3D model of the lumbar area, through magnetic resonance and computer tomography, to obtain the soft tissues and the vertebraes (L2-L5). Its hardware consists of a Novint falcon with a modified end effector, a processor unit, a monitor and a base platform. The profile force obtained with the simulation was compared with a real procedure. The force obtained was according to the movement, if there is no movement, there is no force, also the initial point and direction of the penetration is fixed, and all the applied force will be in that direction. After the simulator was integrated, five anesthesiologists evaluate some subjective parameters such as graphical quality, needle motion tracking quality, and similarity with a real patient, the results showed that the graphical component and the needle movement quality were near of excellent. Fig. 8 shows all the components of LP Sim.

Fig. 8. Components of the simulator LP Sim [5].

In [19] Serra et al developed a simulator, as a serious game, using Unity3D and blender to create the VE through the SCRUM methodology. The VE consists in four phases, the objective of the first one, the presentation phase, is to familiarize the user with the simulator; the second one, the formation phase, shows passively anatomical and technical knowledge; the third phase, the learning evaluation, the formation is evaluated and the simulator indicates if the user is qualified to practice the LP; and finally, the practical phase, the user trains the LP. The authors modeled the vertebraes, a patient, a needle and a surgical table (see Fig. 9). The LP procedure is not explained in detail, and the paper does not mention if the simulator needs another tools like a haptic device or a controller. An advantage of this simulator is that an expert defines the parameter of the training for a personalized and incremental training, however, authors did not mention what parameters can be defined. On the other hand, this simulator has not been tested.

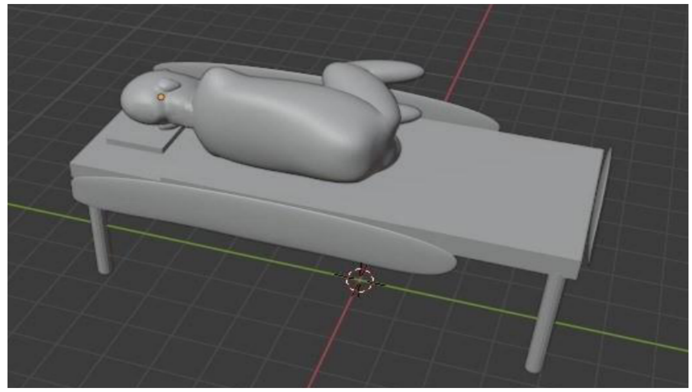

Fig. 9. Serious game for the LP training [19].

III. Commercial simulators

Nowadays there is only one commercial virtual LP simulator, and it is a mixed reality approach, using virtual reality and augmented reality. The name of this simulator is Sim&Care Lumbar Puncture Simulator and is manufactured by InSimo company [20]. Its development was done in collaboration with the Rheumatology Department at Strasbourg University Hospital. Sim&Care represents different anatomies and simulates the resistance of the different tissues through a haptic device, but the company does not mention the haptic algorithm that the simulator uses. In the last version, the company incorporate the capacity to monitor the patient's emotions and reactions according to the procedure. According to the company's web page, there are different plans to purchase the simulator, it can be used with the institution equipment, can be rented or totally bought. The equipment of this simulator consists of a PC, an optical device, augmented reality glasses and an audio device (see Fig. 10). Although the characteristics of the required devices are not specified, in the demonstrations they use the Phanton Omni. In addition, the simulator includes metrics for a defined assessment, defined with the help of doctors, physicians to observe the user's performance, although it is not specified in what these metrics consist of.

Fig. 10. Lumbar puncture simulator Sim & Care [20].

IV. Discussion

This section will compare the simulators presented in Sections II and III, mentioning the advantages and disadvantages of these systems. Table I shows the main characteristics of the virtual LP simulators like the type of haptic device, the DoF to provide force feedback, the models used in the VE and number of patient variations.

In order to achieve a more realistic experience, the use of haptic devices has been implemented and this can be observed in nine of the 10 simulators presented in this article, where [19] is the only article where the use of a haptic device is not mentioned. The haptic device used in each system varies since all of them uses different commercial devices. In four of the 10 simulators [15], [5], [20] the devices monitor and provide force feedback in 3DoF, which means that the translation of the virtual needle can be modified according to the translation of the haptic device, and the user receives the force in X, Y an Z axes. On the other hand, two simulators [13], [14] provide force feedback in 3DoF and allow 6DoF movements, providing the possibility of observing the current rotation of the needle according to the rotation of the haptic device and also to modify and represent the angle of the insertion of the needle inside the body, but this angle can be modified at any time since there is no force to fix it. Finally, one simulator [6] uses a haptic device that provides force feedback and allows 6DoF movements, whose benefits are the possibility of fixed the angle of insertion of the needle and provide constraint forces in the end effector of the haptic device which will be reflected in fixing the angle of insertion and eliminate the possibility of change it when the needle is inside the body.

In general the use of a haptic device allows to provide an accurate force feedback, but this force will depend on the characteristics of these devices. One of the limitations mentioned in [6] is the force rendered when the user collides with a bone, since the haptic device provides a maximum of 8.5 N as a peak, and the continuity of the interaction with a bone can not be simulated. However, the use of haptic devices provides the possibility of calculating the interaction forces between the patient and the needle, according to the biomechanical behavior of the tissues, or to imitate a force profile obtained from a real LP.

VE is the other component of a VR simulator, and it provides different tools and advantages. First, the use of a VE allows modeling of different tissues or areas of the human body, and the simulators presented in this article use a similar anatomical model, all of them focused in the lumbar area with the skin, bones and some soft tissues. Furthermore, four of the anatomy models [6], [15], [5], [18] were created with medical images for a realistic representation of the anatomy, but the disadvantage is that these models represent an specific anatomy, because the data were collected from an specific person. Second, the use of virtual models offers the opportunity to modify specific zones or tissues, providing the capacity of represent different anatomies and conditions, like elderly, calcification of the ligamentum flavum, and obesity. In the comparison of the simulators, only two of them have the option of choose between two or more patients and therefore the possibility of training with two anatomical variances. Finally, another advantage in using a VE is the possibility of evaluating the skills of the user with quantitative data and not to rely in the observation of the experts. For instance, the number of successful punctures, the time of the training, the trajectory, the number of unwanted collisions (bones).

One of the advantages of the mannequins over the virtual simulators is the possibility to train the palpation, which is an important step in the LP. This step has not been considered for most simulators, and just one [17] tried to replicate it with a haptic device, but in [13] authors used a mannequin, although it is not clearly stated that palpation is its objective.

The evaluation of a simulator is important to validate its performance and its capacity of training medical students. The usability of some simulators [14], [18], [5] was evaluated, and from this evaluation authors could detect some improvements, such as enhance the haptic algorithm, refined the fluoroscopy images, and improve user experience. On the other hand, just one article [6] describes the evaluation of the simulator to validate its functionality for training proposes. Finally, one of the 10 analyzed simulators is commercially available, Sim&Care [20] by InSimo, with different prices and plans to acquire it.

V. Conclusions

The development and use of virtual simulators look for a realistic training, in order to overcome the advantages offered by the mannequins, such as the palpation, the possibility of leak CSF if the dura is pierced, the possibility of remove the skin and look inside, and the physical similarity with a patient [8]. The LP virtual simulators mentioned in this article have proposed solutions to meet these characteristics and to provide more, such as immersion and different biomechanical behavior in tissues.

The simulators presented in this article have shown different characteristics that try to simulate a realistic situation for a LP procedure, but exists the potential of improve these systems, to provide a realistic and functional training. If these characteristics are put together in a simulator it can result in a system with benefits for the patients and the physicians. The physicians could train in a safe and controlled environment, and it will be reflected in a successful procedure on patient.

After the comparison between these simulators, some characteristics were detected, and can be combined in order to develop a more realistic LP virtual simulator and provide a better training to the user in a controlled and realistic environment, resulting in a successful and safe procedure. An important point to consider and probably, the most noticeable difference with the mannequins is the palpation, this characteristic must be considered in training, not necessarily within the VE but as a complement to the simulator. The 3D models of the VE has to consider the lumbar zone with the landmarks and its tissues, these models have to be anatomically correct. In addition, the simulator should has the possibility of choose between patient

TABLE I

A COMPARISON OF TEN VIRTUAL LUMBAR PUNCTURE SIMULATORS

Simulator	**Haptic Device (DoF force feedback/DoF)**	**Modeled anatomy**	**Patient model**	**3D Models**	**Visualization**	**Evaluation module**	**Palpation**	**Adjustable needle insertion point**	**Patient variations**	**User experience evaluation**	**Evaluation as a training tool**
Gorman et al. (2000) [13]	Phantom 1.5 desktop (3/6)	Spinal canal area and column, six tissue layers	Layers modeled	Virtual needle and patient anatomy	NM	Playback of the training record	✓	✓	1	X	X
Farber et al. (2009) [6]	Phantom Premium 1.5 (6/6)	Skin, bones and soft tissues	Created from CT Data	Virtual needle and patient anatomy	Monitor	Recording, comparison with optimal path, score from 0 to 100.	X	✓	2	X	✓
Jiang et al. (2013) [14]	Phantom desktop device (3/6)	Skin, muscles, ligaments	NM	NM	Monitor	Immediately feedback give it by an expert	X	✓	1	✓	X
Day (2014) [15]	Novint Falcon (3/3)	Spine, pelvis, and torso	Created from CT data	Patient anatomy	NM	NM	X	X	1	X	X
Wang et al. (2017) [16]	NM	Organs	Modeled according to the puncture	Patient, nurses, physician, surgical instruments, operating rooms.	Monitor and HMD	Number of trains, completion rate, average finished time	X	NM	1	X	X
José et al. (2018) [17]	Phantom Omni /Novint Falcon (3/3)	Spinal column (L1 to the sacrum)	NM	Human hand and lumbar needle	Monitor	X	✓	✓	1	X	X
Fluoroscopy Guided Lumbar Puncture (2018) [18]	ImmersiveTouch Platform (NM)	Lower torso model	Created from CT datasets	Virtual needle and patient anatomy	Stereostopic interaction	NM	X	✓	NM	✓	X
LP Sim (2020) [5]	Novint Falcon (3/3)	Lumbar area	Created from CT and MR	Virtual needle an patient anatomy	Monitor	NM	X	X	1	✓	X
Sim&Care (2020) [20]	Phantom Omni (3/3)	Skin, bones, and tissues where the needle passes	Not mentioned	Patient anatomy	HMD, Augmented reality	NM	X	✓	Minimum 4	NM	NM
Serra et al. (2021) [19]	NA	Vertebraes	NM	Chirurgical table and lumbar needle	NM	X	X	NM	1	X	X

NM = Not mentioned, NA = Not available

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variations, or the possibility of change the biomechanical behavior of the tissues in order to represent different situations. Also, the skin can change its opacity to visualize the inner part of the area, and a representation of the CSF leak should be integrated. Moreover, the use of a haptic device is required to provide a realistic experience, ideally a device that provides feedback in 6DoF should be used to represent the angle of insertion.

Finally, a user experience evaluation has to be performed to confirm the usability of the system, also, an user study must be carried out to confirm that the simulator works properly as a training tool. As mentioned above, researchers interested in developing a LP simulator can identify the best software and hardware for the design, development or selection of the virtual environment and the haptic device.

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