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Haptic interaction for needle insertion training in medical applications: The state-of-the-art

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ABSTRACT

Computer-based simulation for medical procedures training has been gaining relevance, as well the use of haptic devices for developing fine motor skills in such simulations. The purpose of this paper is to present a review of the state-of-the-art in virtual needle insertion training simulation based on haptic interaction. A systematic review method was applied to gather documentation that enables a rigorous audit of the process stages and results. We established a classification system based on certain characteristics of the studies analyzed, including: main procedures and target body regions in medical applications; ways to generate haptic feedback; devices; types of environment; and user validation. In addition, the review aimed to identify challenges and trends in the field, indicating research opportunities. Results showed the predominance of Virtual Reality and commercial haptic devices in simulations. Since most studies are based on subjective tests, finding ways to objectively evaluate haptic interaction perception represents a promising research field. We also found that devices and ways to generate haptic feedback and to represent tissue and needle behavior pose limitations and challenges for computer simulation. Finally, the realism provided is a constant concern in the validation process, which brings another problem: defining and performing suitable user tests.

Contents

Abbreviations: ASQ-IBM, After-Scenario Questionnaire - International Business Machines; ANOVA, Analysis of Variance; AR, Augmented Reality; w, Bandwidth of the stiffness matrix; $O(\text{size of the data input})$, Big-O; CHAI3D, Computer Haptics and Active Interface; DoF, Degrees of Freedom; DoFF, Degrees of Force Feedback; FEM, Finite Elements Method; GEARS, Global Evaluative Assessment of Robotic Skills; H3DAPI, H3D Application Programming Interface; HMDs, Head-Mounted Displays; Hz, Hertz; JND, Just Noticeable Difference; LEM, Long Element Models; mm, Millimeters; NASA TLX, National Aeronautics and Space Administration Task Load Index Assessment; N, Newtons; n, Number of nodes of the stiffness matrix or number of particles; PAFF, Point-Associated Finite Field Approach; PCMFS, Point Collocation-based Method of Finite Spheres; PSE, Point of Subjective Equality; PMRE, Point of Motor Response Equality; QoE, Quality of Experience; TI, Tangible Interface; 3D, Three-dimensional; 2D, Two-dimensional; UVA, Urethrovesical anastomosis; VR, Virtual Reality.

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1. Introduction

In the healthcare area, practical lessons are important to ensure that medical and clinical procedures are well understood, since poorly executed procedures can be harmful to patients. In the United States, medical errors are the third leading cause of death, behind cancer and heart disease [1].

Thus, student training is a fundamental activity which often follows the Halstedian Apprenticeship model since the early 20th century. More recently, there has been increasing interest in the integration of simulation-based training in curricula [2]. These can involve from mannequins and tangible objects to computing and hybrid systems, with a growing use of computer systems [3]. These technologies can reduce risks for patients [4,5], increase the apprentices' certainty [6–8] and enable the execution of automated user performance assessment [9]. Moreover, these technologies can provide several levels of training, with different situations and degrees of difficulty [10], and minimize or eliminate the cost of keeping physical laboratories with infrastructure consisting of animals or cadavers [11,12]. There are anatomical differences between animals and human beings [13], as well as ethical issues involving their use [5,12]. Although cadavers offer physical presence when compared to a simulation performed only with a computer, they have physiological differences in relation to living organisms [14].

Another benefit of computer-based simulations is the high number of possible training repetitions without the wearing of materials, as is the case of training using cadavers [15]. It also offers flexibility when comparing virtual objects and real objects, since the latter, for example mannequins, offer a physical presence but provide limited replications of physiology and anatomical variations [5]. Hybrid simulations allow combining real and virtual objects [16]. In addition, these simulators can offer functionalities that favor assessments and feedback to apprentices.

The traditional use of cadavers and animals remains important [17]. However, technologies such as computer simulations are considered important ways of training [9], especially those offering haptic interface [18]. The term haptic comes from the Greek word *haptesthai*, meaning sense of touch [19]. The sensation of touch is triggered when the skin is subjected to mechanical, electrical, thermal or chemical stimuli [20]. The haptic sensations can be classified into two categories according to their nature [21]:

- tactile feedback: sensation that indicates the characteristics of the surface of objects (temperature and roughness) when in contact with the skin;
- force feedback: weight or resistance feedback, involving kinesthetic or proprioceptive aspects related to the perception of movements based on body parts, such as muscles, tendons, joints and ligaments; latter aspect can also include posture and body balance information.

The role of haptic interaction in healthcare has three subareas [22]: (1) haptic human perception and motor performance as a relevant factor in the performance of medical tests and procedures; (2) the role of haptic systems in training and evaluating clinical skills; and (3) the use of haptic systems to improve medical interventions.

Training simulations with haptic interface are currently used for various medical procedures and in various medical specialties, and they can be grouped into six main categories: (1) palpation, (2) laparoscopy, (3) endovascular procedures, (4) endoscopy, (5) arthroscopy and (6) needle insertion [5]. Although these categories are defined as procedures and tasks in Coles et al. [5], in this text they will be classified as groups of procedures with a main task. Thus, the needle insertion group will be studied with several procedures that mostly involve the insertion task.

Needle insertion is relevant because it is an important task in many simulated medical procedures. Categorizing studies and identifying problems, opportunities and trends are important contributions given the growing demand for simulations of medical procedures. In addition, the needle insertion group is related to other procedure groups, such as palpation (which assists the needle insertion task), laparoscopy and arthroscopy (involving needle insertion at the suture stage), and endovascular procedures (which start with needle insertion). Needle insertion involves several skills, such as navigation, as well as handling needle steering and deformation during the insertion, using an image or a sequence of images; insertion with palpation; or insertion and extraction only.

2. Methodology

In this paper, we conducted a systematic review of the literature according to established methods [23]. In this systematic review the formulated search question was: what is state-of-the-art of needle insertion simulations for training using haptic interface? The languages used were English and Portuguese; the keywords were *Needle, Haptic* and *Training*. The scientific search databases used were IEEE Xplore (Institute of Electrical and Electronics Engineers)[1], ACM Digital Library (Association of Computing Machinery)[2] and Scopus[3].

The inclusion criteria were: the study should be published as a short or full paper, describing the following topics: haptic approach, needle insertion and training. The exclusion criteria were: the paper is repeated, the paper exclusively deals with teleoperation using haptic interface (not aimed at training, but directly at the performance of a surgical procedure), the paper is not related to the needle insertion task (only with palpation or other tasks).

After applying the aforementioned criteria to the papers retrieved by database search mechanisms, 145 papers were included and 168 were excluded. Tables 2, 3 and 4 (Appendix A) list the papers included after each database search (most recent first), indicating categories and subcategories. The difference between the terms "No" and "? (question mark) + Information" used in the tables is that the former indicates absence and the latter refers to unspecified information.

We analyzed the results taking different categories into consideration: types of environment (grouping studies according to the technology used to build the environment – virtual, tangible or both); medical applications (gathering research work developed for the same healthcare area); devices (analyzing investigations according to the characteristics of the haptic devices used); ways to generate force feedback (discussing papers considering the characteristics of the models and methods used to compute feedback provided to users and defining tissue and needle behavior); and user validation (analyzing how the works were evaluated – objectively or subjectively – as well as the number and experience of testers). The categories were specified based on important information from the papers included, allowing us to detail and organize the data extracted. Fig. 1 shows the categories (vertical text boxes) and subcategories (horizontal text boxes). The following sections present results and discussions about the categories, considering the subcategories and how they relate with each other.

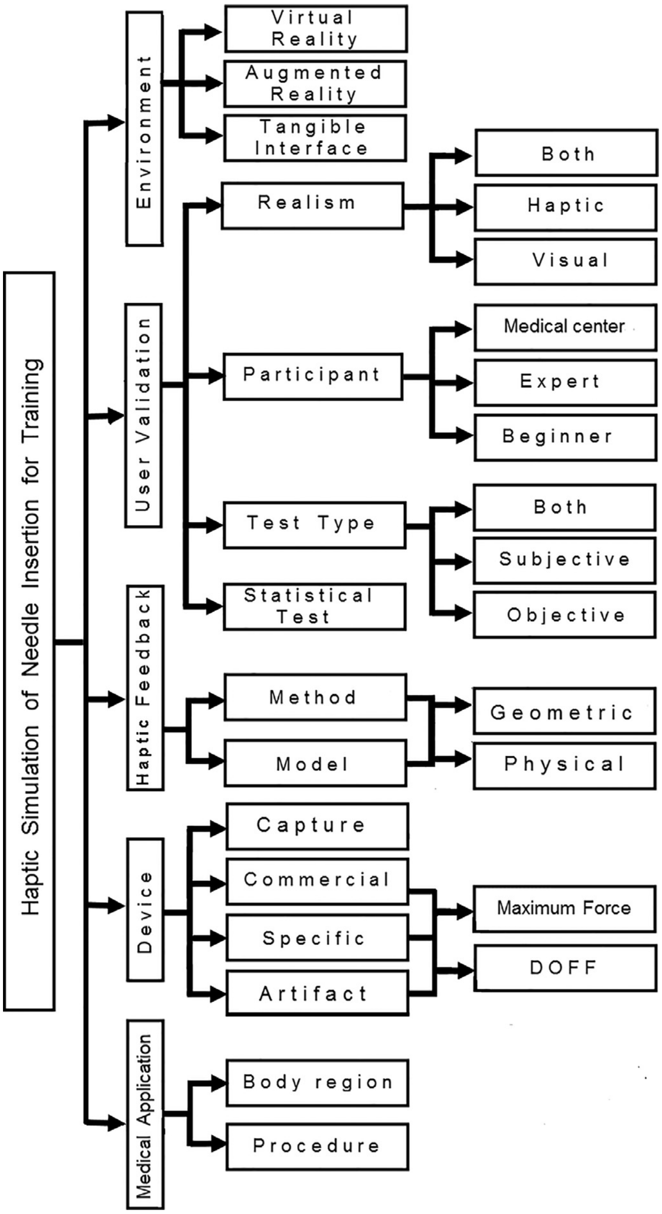

Fig. 1. Proposed categorization of the papers included.

3. Types of environment

The types of environment were classified as Virtual Reality (VR), Augmented Reality (AR) and Tangible Interface (TI). The VR subcategory refers to systems that enable real-time human-computer interaction in three-dimensional (3D) virtual environments [24], even with the use of ordinary video monitors and no Head-Mounted Displays (HMDs) or special glasses. The AR subcategory comprises environments with virtual and real elements and real-time 3D human-computer interaction [25]. TI contains physical elements only, with no virtual elements or computer generated objects.

VR was the predominant type of environment (63.9%), followed by AR (13.6%), TI (7.5%), and some papers did not present environments. VR-based environments are suitable technologies for training because although synthetic bones and muscles (TI) can mimic physical properties of these objects, they may experience some wearing after a period of use or repetitive use. This wearing may hinder the correct simulation of tissues and organs after a training period or a training session, and a set of physical objects is necessary to replace inadequate materials. Additionally, virtual objects enable greater flexibility for anatomical variation and physiological replication when compared to synthetic objects [5], even with the growing use of 3D printers.

On the other hand, it is important to simulate changes in tissue behavior during the training session, such as loss of elasticity or another property of the skin after being pricked by the needle several times. Thus, the models for providing haptic feedback must consider this phenomenon to obtain realistic simulations (Section 6).

Most of the studies conducted in the VR category chose commercial haptic devices for haptic interaction. Notwithstanding some of the constraints related to this category of devices, their cost-benefit relation can justify their choice. Some have relatively low cost, in addition to offering the possibility of customization (Section 5).

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[1] http://ieeexplore.ieee.org/Xplore/home.jsp.

[2] http://dl.acm.org/.

[3] https://www.elsevier.com/solutions/scopus.

There are constraints with TI as well, considering it is difficult to determine the amount of time, number of sessions or repetitions that materials can endure before causing problems during training, when they should be simulating tissues and organs, and providing haptic feedback (Section 6).

However, these materials provide physical presence and can be an alternative to bones. We have observed that the authors of the studies included in this category generally developed their own devices, described as artifacts in Section 5.

Regarding AR, 3D registering, i.e., 3D alignment between real and virtual objects [25], is still a complex problem. In this type of environment, the use of internal images (synthesized or real) overlaid on the patient's body or physical objects that represent parts of the human body can be useful in training and planning procedures. It enables combining real and virtual elements, e.g., physical parts and graphical objects in real scale parameters to guide spatial perception, which enable trainees to observe distances, obstacles and vital parts in the real world. It can also prevent the wearing of anatomical structures, because in this case, the needle and structures can be virtual objects (dynamic and deformable) overlaid on a physical object (stationary). An example of the use of AR is shown in Sutherland et al. [16], which described a system using a Finite Elements Method (FEM) for simulation, as well as a display to present an internal view of the spine overlaid on a physical object that represents the structure of a human body. The type of device most frequently used in this subcategory of environment is also commercially available. Since the main aspect of this type of environment is to combine virtual and real objects, the devices are not different from those employed in VR applications, as seen in Section 5.

The images used to build 3D objects can be employed in VR and AR environments, bringing in objects that are similar to a real patient. However, in AR, these virtual objects can be overlaid onto the actual patient or physical objects, e.g., an environment close to the real world. An AR environment was designed with 28 real cases [26] and two VR environments provided 50 real cases [27] and 8 cases [28] for training. A problem in the image acquisition process for building 3D objects is the displacement of injuries and vital regions due to the respiratory movement [29]. There are no studies comparing both environments in needle insertion training [30].

Finally, the use of a 3D object to represent the user's hand or arm in VR environments has not been widely explored [31–33] and this could assist the user when handling the needle or syringe. Few studies applied collaborative systems to their training. The approach involves an online interaction between student and professor by using two haptic devices [32,33].

The following are the human sensorial modalities explored in needle insertion training virtual environments: visual, haptic and auditory. Other modalities, such as smell and taste, were not found. Visual and haptic are widely used in the mentioned above VR and AR projects, and auditory was found in only one study [34]. Game concepts were explored in a small number of studies [35–38] and in some studies the term "gamification" was found [39–42].

4. Medical applications

Although our protocol did not include keywords restricted to medical applications, all the studies found were related to this subject. We analyzed the procedures simulated and the target body regions of the procedures in healthcare.

In some cases, we did not group procedures that were similar in nature because of the nomenclatures used in the papers, such as (1) telesurgery, microsurgery and surgery; (2) biopsy and injection of fluids/biopsy. In addition, radiological intervention, a type of minimally invasive surgery, was separated from microsurgery, surgery and telesurgery. Telesurgery was added to the subcategory procedures because in a study we found the *simulation* of a teleoperation system [43], given that teleoperation systems are not training simulation systems [22], according to the inclusion criteria (Section 2).

We included some studies that addressed laparoscopic procedures, although in this context, laparoscopy is considered as another group of procedures, different from needle insertion, according to the classification in Coles et al. [5]. This exception is due to the fact that the papers found emphasized the needle insertion task in laparoscopy simulation, specifically at the suturing stage, which requires bimanual interaction and indirect needle manipulation [35,44]. Certain studies involving catheterization (group of endovascular procedures, different from needle insertion) were also included, since the procedure begins with insertion of a needle [45].

Similar to the procedures subcategory, target regions were analyzed separately according to the terminology used in the papers, separating: blood vessels and arm (in this case, the targets are the blood vessels of the arm); spine and lumbar region. Various procedures and target body regions were observed, especially brachytherapy (prostate), cell injection (cell or ovum), anesthesia and biopsy, and the last two involved various body target regions. We found veterinary medicine studies, that involved optometry and intravenous injection procedures [30,46]. It can be observed that there are several fields in the medical area regarding the different procedures and target body regions, which may change the requirements to develop needle insertion training systems. This can be motivated by the differences in how procedures are performed, as well as the needles and specific tissue features (Section 6).

With regard to the spine, there have been important contributions involving AR environments (Section 3). Hollensteiner et al. [47] presented an AR-based surgery simulator that uses synthetic soft tissue blocks on a real object that represents a human body, in order to provide more realism and a proper haptic feedback during the procedure, as described in Sutherland et al. [16].

In certain procedure simulations, needles were used together with other instruments, such as a transducer or probe. The tasks related to needle insertion training can involve hand-eye coordination because many techniques use medical imaging to help guide the needle insertion. In several situations, this task focused on certain skills depending on the desired training, such as: image interpretation (makes use of previously captured images instead of real-time to find the appropriate needle insertion) [44,48–53]; and needle navigation in two ways - the first one with radiographic guidance, e.g., real-time images acquired by other instruments [27,34,37,40,45,47,53–75], and the second one with palpation to guide during the insertion [10,26,32,33,76–85].

Conversely, certain tissue simulations were not found in the studies included, for example, tissues bearing pathologies. This could increase the complexity of developing medical systems, because the haptic feedback models (Section 6) for devices used in VR and AR systems (Section 3), as well as the artifacts (Section 5) used in AR and TI systems (Section 3), should take these situations into consideration.

5. Devices

The haptic devices were classified into specific (a prototype or purpose-built device developed in research project), commercial (generic devices available for purchase), artifact (such as a box, silicone or other materials; with or without electrical elements to capture information but not for haptic feedback) and force capture devices (used to analyze the properties or parameters of real tissues or organs). Some studies did not mention devices and described pseudo-haptic techniques of human-computer interaction [85,86].

In the studies, commercial devices were the majority, followed by artifacts, specific devices and capture devices. Although commercial devices are often ergonomically unsuitable for the simulation of some procedures, they were found in many studies most likely due to the availability of software libraries (such as CHAI3D, OpenHaptics Toolkit and H3DAPI), as well as plug-ins for software development platform (such as Unity3D), which provide practical ways to include them in applications. Additionally, in some of them – like the Phantom Omni (currently Geomagic Touch) – their parts can be easily exchanged to make them more ergonomic.

Phantom Omni and the Phantom Premium 1.5 class (there are two types of Phantom Premium 1.5, with differences in DoFF (Degrees of Force Feedback) and costs [5]) were more widely used. This was probably due to their cost-benefit relation, since the Falcon has the lowest price but, compared to other two, it has a lower DoF number (Degrees of Freedom), as well as a smaller workspace. The Falcon has a higher force feedback than the Phantom Omni and Phantom Premium 1.5; however, it is very close to the Phantom Premium 1.5 (9 and 8.5 Newtons (N), respectively). Additionally, the Phantom Premium 1.5 has a larger workspace than the Phantom Omni, $191 \times 267 \times 381$ and $160 \times 120 \times 70$ millimeters (mm), respectively, for the x, y and z axes; and greater maximum force (3.3 and 8.5 N); however, it has a higher cost.

The workspace of a Phantom Omni is limited when compared to other devices, which could be a problem for some needle insertion motions requiring larger workspaces [87]. There were cases that demonstrated the limitation of devices to faithfully reproduce the suitable haptic sensation was verified, given that both the DoFF and the force feedback maximum values were insufficient for the task [10]. These problems have been overcome in some cases with the use of devices that have more resources (larger workspace size, higher number of degrees of freedom for motion and force feedback, higher force maximum value) [60,88]. Thus, it is necessary to analyze each procedure, the body region and actions required in the needle insertion task to determine whether a device is suitable for a certain application. Considering the force maximum, Phantom Omni provides 3.3 N and it was not employed in procedures involving the ligamentum flavum, a region which requires higher force values for suitable haptic sensation (15 N [89]). Regarding DoFF for needle insertion simulation, one degree of freedom may be sufficient in certain situations; three degrees may be sufficient for insertion simulation in a single region; however, five degrees are required for correctly simulating arbitrary regions [5]. The most widely used device (Phantom Omni) has three DoFF. Thus, the needle insertion task can be simplified or simple actions of the needle insertion task can be chosen, such as motion in one direction, to allow this type of device and reach the desired training or desired skill acquisition. We found studies that simulated needle insertion with one DoFF [43,48,49,51,60,81,90–94], two DoFF [27,28,52,60,62,63,68,79,95–100], three DoFF [26,31,35,44,61,64,70,83,101,102], four DoFF [67,103], five DoFF [29,75,104] and six DoFF [16,30,32,36,37,45,50,59,72,80,84,105–118].

We observed that the development of specific hardware to simulate needle insertion procedures was not widely explored. One reason for this can be the lack of a specific market hence enabling scale production. Given the growth of procedures simulation for medical training, the development of specific hardware is a challenge that can become an important research opportunity.

Haptic devices can be classified according to intrinsic mechanical behavior. "Impedance" haptic devices read position and send force and "admittance" haptic devices read force and send position. The first category is simpler to design and much cheaper to produce. Admittance-based devices are generally used for applications that require high forces in a large workspace [119]. In this survey we observed which impedance-based devices are most widely used. An important research concerns the development of needle insertion applications for some procedures (kyphoplasty, for example) with admittance-based devices and analysis (in comparison to impedance-based devices).

The ergonomic aspect of the devices is still a limiting factor for haptic realism in the simulation, which is a challenge to be overcome, since real syringes and needles do not have coupled arms, as most haptic devices do. In some of the simulations found, the arms of the devices were visible by users, since the virtual environments were not immersive and common video monitors were used, which could be solved by using HMDs, devices used in VR and AR systems.

We analyzed that modifications of commercial devices were ways to overcome limitations, such as the format of the instruments, replacing the stylus of the devices with syringes [56,57,80,115,120–124], especially in the case of Phantom Omni. Another way to overcome the workspace constraint of the Phantom Omni was a change made to the x and z axes, since the available space of the device's x in millimeters is larger than the z axis, but the simulation of certain actions of the needle insertion task is characterized by large movements in the z axis [34].

The use of physical objects (artifacts) to represent anatomical structures instead of robotic equipment was noted (TIs in Section 3), with force values varying between 6.0 and 250.7 N, such as: 6 N for synthetic tissue and 80 N for synthetic bone [49]; 7.67 and 7.66 N for synthetic muscles [47]; 14 N [44] for synthetic tissue; and ranges of 198.5 to 242.3 N, 198.5 to 242.3 N and 191.5 to 250.7 N [125] for synthetic vertebrae. A small number of studies employed devices that exceeded 20 N, with many force values between 3 and 9 N, a range that includes the most widely used devices: Phantom Omni (3.3 N), Phantom Premium 1.5 (8.5 N) and Falcon (approximately 9 N). As mentioned above (Section 3), further studies are needed to address the wearing of these physical materials after a period or training session. In addition, the artifacts must be chosen carefully to represent the tissue properties, including their pathologies.

The precision of the haptic devices depends on its characteristics, and coupling the rendering speed and force calculus at the correct moment, allows the user's high sensitivity and allows reaching the realism, but increases the costs. Depending on the procedure, high force feedback is necessary (for example, spine procedures); DoF and DoFF are important to allow movements and feedback in various directions, and resolution is relevant to capture fine movements and provide fine vibrations for accurate procedures.

Table 1 shows the main commercial devices and characteristics (DoF, DoFF and costs), as well as the number of studies that used these devices. There is a range of prices when a device class has different characteristics.

Capture devices are important to define parameters for haptic models (Section 6). In this case, apart from calibration, the pieces (animal parts) or whole organs must be chosen carefully to capture tissue properties. For example, forces during hypodermic needle insertions in human skin and rabbit's ears (both in vivo) were qualitatively described [126]. Physiological problems can be encountered, since these parts may be different when the animal is alive or when other body parts influence the work. Thus, studies must be conducted to investigate the differences between living and dead tissues in needle insertion [126]. Additionally, pathological parts could be included in the studies, in order to represent

Table 1
Main commercial devices ordered according to the number of studies that used the devices.

Device	Number of studies	DoF	DoFF	Euros ×1000
Phantom Omni	48	6	3	2
Phantom Premium	26	6	3 or 6	18 to 70
Novint Falcon	8	3	3	0.2
Phantom Desktop	8	6	3	11
Delta	3	3 or 6	3 or 6	22 to 40
Cyberforce	3	6	3	45
Virtuose 6D Desktop	3	6	6	30
Quanser 3DOF	2	3	3	25
Omega 6	1	6	3	14 to 24

several types of tissues or organs for diversified training; as well as different needle angles during the capture.

We also analyzed the use of more than one device for a simulation and we highlight the following studies that use: identical devices in the same project [32,33,57,57,67,73]; different devices in the same study [37,64]; and both (identical and different devices) [60,62,63].

The use of two devices was common in the simulation of two important instruments for certain procedures: the needle and the transducer/probe, enabling to visualize medical images during the procedure; or to simultaneously simulate palpation and needle insertion. The devices based on force feedback were the majority, compared to tactile devices [21]. However, there are research works describing tactile devices that help movements, such as a vibrotactile guidance sleeve to help the users (position and orientation of the needle) [127]; a wristband to help during the needle trajectory in order to reach a desired point in brachytherapy procedures [128]; an Omega 6 to produce kinesthetic and vibratory feedback to provide navigation cues about the needle's correct position and orientation [97].

Finally, training in computational systems can be advantageous in medical education since some procedures are performed indirectly using robots. Thus, the experience with devices can be relevant in the learning process.

6. Haptic feedback

This section comprises ways to generate haptic feedback, including models and methods that enable determining the haptic feedback and the behavior of tissues and needles (for example, deformations). They are used when there is contact between tissue and needle, in the pre-puncture or deformation, puncture or rupture, relaxation, and extraction phases considering one or more layers of tissues [129].

A model is an abstract structure that uses mathematical concepts to describe the behavior of a certain system. In the current context, the models describe haptic feedback and the behavior of the virtual objects (tissues and needles). The methods indicate ways in which the models can be implemented in a digital computer.

For better clarity, this section was divided in subsections: models; methods; tissues and needles; and smoothness and interpolation techniques in the rendering.

6.1. Models

The most frequently applied needle insertion models found were Hooke's Law, friction (Coulomb; Karnopp; or only static or dynamic, depending on the term used), and Kelvin–Voigt. In most cases, more than one model was employed in the same study, because many parameters of the needle and anatomical structures must be taken into account for force feedback.

We found iterative or incremental development of models, such as the model based on Choi et al. [130], which was found in Chan et al. and Zhang et al. [37,84] and the variation of the Voigt model [131], also found in Ni et al. [64] and Ni et al. [72]. The model found in Okamura et al. [132] was used in several studies [81,92,124,133].

The models are characterized by mechanical properties (elasticity, viscosity and plasticity) and the phenomena which can influence their behavior (creep, stress relaxation and hysteresis) [134]. These phenomena consist of a constant load or force for a period of time; stress relaxation is the reduction of tissue material resistance by constant deformation; and hysteresis is the loss of energy in the form of heat [134,135]. The models can require different parameters, such as mass, Young's modulus, Poisson ratio and Cauchy's tension to provide mechanical behavior. Different models vary regarding the number of required parameters. We observed that in some situations, two or more models were used to represent different tissues, such as in cell injection studies [91,93,94,136]. Some studies were carried out to obtain material parameters that could be applied to the models.

Some projects found in this review used physical or synthetic tissues instead of computational models for haptic feedback. One example is the study of Hollensteiner et al. [47], which described the development of synthetic muscle blocks made of silicone rubber to integrate an AR simulator. However, there is continuous effort to achieve more efficient implementations that allow real-time interaction with highly detailed 3D objects and the need to obtain physical parameters from real body tissue remains, at least for physically-based models [132].

Linear models are common in some studies. Linear elasticity models are computationally cheap, but they are not suitable for large deformations because they make elements expand artificially in the simulation. In addition, the linear response from a Voigt element in the Chinese acupuncture procedure simulation did not match the non-linear force-deformation behavior of the skin [116]. Other models were not employed, such as: Kelvin–Boltzmann, Huntâ;;Crossley, Fractional and model based on Ogden strain energy [137]; and LuGre model for friction [89]. The Hunt–Crossley is more adequate to simulate viscoelasticity than Kelvin–Voigt; and Coulomb friction presents the uncertainty of the friction force at zero velocity [89].

Brett et al. [131] created a model based on viscoelastic functions; Barbé et al. [138] and Maurin et al. [139] obtained fits using various functions; Simone and Okamura [132] described the needle force as the sum of the cutting force, the stiffness force and the friction force. Since these models cannot represent combinations of tissue types and needle geometries, each medical application or tissue layer representation requires a new set of parameters. The models are fit to experimental data and may represent the effect of crack formation during needle insertion, but they cannot model this effect with underlying physics and are dependent on the choice of units [140].

Thus, there are studies which consider models based on energy or on the description of the mechanics of crack formation. The effects of a needle geometry when it interacts with tissue properties causes permanent changes at cell and membrane scale, creating new surfaces or damage inside a tissue. This damage while the needle is piercing and cutting is calculated as a function of the average over the surfaces and over time. In this category of models, there is the fracture-based mechanical model [140,141]. When a sharp object or a needle penetrates a tissue, a crack propagates at its tip, interchanging energy among four phenomena: the work done by the needle, the irreversible work of the fracture, the work of friction and the change in recoverable strain energy. An energy balance during insertion assumes the following: (1) elastic fracture, where the tissue deformation is plastic only in the neighborhood of the crack; (2 quasi-static process, the kinetic energy can be neglected, the velocity is low enough for the equilibrium of the system throughout the entire time; (3 sharp needle interaction, where the needle tip is always in contact with the crack; (4 constant crack width. For sharp bevel tips, the crack size is similar to the diameter of the needle; for less sharp and short bevel, the crack size is larger than the needle diameter, with a larger insertion force [140]. Fracture-based mechanic approach was applied to model the haptic feedback in one study [113].

6.2. Methods

The methods can be classified, like the models, into: geometric methods, which include mathematical foundations such as control points or parametric forms (Spline, B-Spline and Free-Form Deformation); and physical methods, which include principles of physics such as dynamics and continuum mechanics, involving mechanical properties (FEM and Mass-Spring) [142]. Geometric methods usually use less computational resources and their implementation is considered simpler. However, they provide low realism, since they do not allow the simulation of mechanical properties [143]. On the other hand, the simulation of physics-based deformable objects is not a trivial problem, since these structures have specific characteristics such as non-linearity, viscoelasticity, inhomogeneity and anisotropy [144]. Viscoelasticity, inhomogeneity and anisotropy mean that soft tissue properties are time-dependent functions, they vary throughout tissue thickness and they vary with direction, respectively [129]. The nonlinear stress–strain relationship results in forces that are not linearly proportional to needle displacement.

The FEMs, albeit suitable for simulations of tissue characteristics, require high consumption of computational resources [144] and simulation systems based on VR and AR are defined by human-computer interaction in real-time [24]. FEM computational complexity is $O(nw^2)$, where n is the number of nodes and w is the bandwidth of the stiffness matrix [145]. The Mass-spring method is conceptually simple and consumes few computational resources [146]. Mass-spring has a complexity $O(n)$, where n is the number of particles [147], which is much smaller than FEM, but its use in simulations does not provide realism both in visual and haptic feedback. Moreover, some techniques are employed to reach these requirements in the FEM case such as: condensation technique (2D to 3D), applying the local remeshing and recomputing the regional stiffness matrix in the regions where there is contact between tissue and needle tip [60]; boundary condition [16,99]; off-line computation [136]; condensation and pre-processing [148]. The FEM equations may be solved using iterative algorithm, whose implementation to store only the non-zero elements of the matrix of size n may reduce the usage of memory resources from an $O(n^2)$ to $O(n)$ [149]. The FEM of [150] was used in [16,68,99]. The method presented in Irving et al. [151] was employed in Chentanez et al. [51].

The FEM was applied in brachytherapy simulations [60,62,63,68,152], but a simulation of this type used Mass-spring [74]. The Strain Mass FEM was implemented in cell injection [91,94,136]. The physiological features, such as respiratory motion, were implemented in some cases [64,70,72,153] and they are important in certain procedures, affecting the haptic feedback and tissue deformation.

Some methods were not found, such as: Long Element Models (LEM), Point Collocation-based Method of Finite Spheres (PCMFS) and Point-Associated Finite Field Approach (PAFF) [154].

6.3. Tissues and needles

In relation to the structures that compose the 3D objects, the methods found involved virtual objects based on spatial subdivision (voxels) [45,60,64,72,73,90,117,155], and based on polygon meshes [10,16,26,39,40,51,58,59,62,63,70,82,84,85,91,93,94,101,104,105,108,116,118,122,133,136,148,149,153,156–169].

The deformation of objects representing tissues or organs received more attention than the deflection of needles. Needle breakages were not reported in the studies. In certain procedure simulations, needles were accompanied by other instruments (transducer or probe). Additionally, we found studies that took the needle tip shape into consideration in modeling and deformation, constituting the bevel of the needle tip [26,51,60,62,63,70], which is considered an important requirement for needle insertion in body regions [126]. Different types of needles can be used with properties' variations, such as format, bevel, tip behavior, which can increase the complexity of the simulation that must reach the realism and real-time rendering rates for haptic and visual feedbacks. The types of needles are usually: rigid [16,26,29,34,47,58,73,79,91,93–95,99,103,105,106,122,133,156,167,170,171] or flexible [51,62,63,82,90,97,109,113,153,167,172,173].

Simulations with flexible needles generally adopted the FEM and its variations. Apart from flexible and rigid needles, researches may consider other needle characteristics such as size, length and thickness.

Different force values are required when puncturing and cutting through each tissue layer with needles. The force values may vary from patient to patient for the same tissue due to prior treatments, age, gender and body mass. In addition, mechanical properties may vary according to tissue condition – healthy, damaged or diseased [129]. Additionally, different types of translational motions in needle insertions showed that to a certain extent, increasing the insertion speed could reduce the amount of tissue deformation. Applying a rotational motion to the needle around its translational axis reduces insertion force and tissue deformation. A higher insertion speed tends to decrease puncture force and increase friction [129].

In experimental studies, insertion forces increased as the needle tip type changed from triangular to bevel and bevel to cone, however, the bevel angle caused no significant effect on the axial force. For each tip type, increasing the needle diameter increased the insertion force [129] and conical needles create higher peak forces than beveled needles [126]. The friction force increased proportionally to the insertion depth according to the needle diameter [129]. The clamping force increases as the needle is inserted into the tissue and the magnitude is affected by the needle gauge and the incision shape [129]. Some studies made reference to needle tip size, such as: 25 gauge [16], 20 gauge [167], 17 gauge [173], 17 and 18 gauge [74], 18 gauge [52,57,59,60,158], 11 gauge [47,49,125], 2 millimeters [174], 0.9 millimeters [168], 25 micro-millimeters [43]. In the case of microneedles, a study analyzing the penetration depth and force of single solid microneedles using various tip diameters (5–37 micro-millimeters) showed that microneedles with 5 micro-millimeters tip diameter were smoothly inserted into the skin (human ex vivo), while the penetration depth of microneedles with a larger tip diameter suddenly increased after initial superficial penetration. The force at insertion increased linearly with tip diameter. Thus, sharp microneedles are essential for well-controlled insertion to a desired depth [175].

6.4. Smoothness and interpolation techniques

Other important aspects in haptic feedback concern smoothness and interpolation techniques, for example: a linear interpolation between constraint planes after each position update combined to a special smoothing filter for force, preventing discontinuities in the force output [133]; a second-order interpolation filter to increase the haptic rate and provide a smooth rendering effect [84]; an interpolation scheme in the haptic loop to allow a smoother user experience in feeling 3D objects [164].

Thus, the haptic update rate is an important aspect of user experience. Although the haptic update rate is 1000 Hz for adequate sensation, there are rates below this value: 10–20 Hz [161], 40–100 Hz [160], 200 Hz [149], 250 Hz [68], 300 Hz [38,171,174], 400 Hz [148], 500 Hz [122,167,173], 500–1000 Hz [37], 500–2000 Hz [59,155]. Studies could be conducted to analyze suitable rates for each application.

7. User validation

In general, the validation of the studies considered two aspects: human validation and technical validation. Although the validation of computational aspects is not the focus of this paper, the statistical test for linear regression was observed, applied to compare the Linear Finite Elements and Nonlinear methods [91,93]; and to compare trajectories [81]. The average and standard deviation statistical tests were used for processing error analysis [70,84,148,149]. It was also important to analyze the processing speed [62,91,93,93,122,148], particularly with respect to the deformation of 3D objects and its effect on the haptic interaction, which must reach high rendering rates.

With reference to user validation, we analyzed the studies included according to five subcategories: types of evaluation (objective or subjective); number and experience level of participants; number of medical centers; statistical tests; and realism analysis.

The biopsy procedure was the simulation that included the highest number of user tests.

Some studies had a learning phase before the experiments, thus enabling users to get to know the devices and systems [36,128,176].

7.1. Objective tests

Regarding the first topic, an interesting point was the difference between objective and subjective tests. Objective tests are related to user performance and skills analysis and subjective tests are related to interviews and questionnaires.

In objective tests, users performance and skills were based on trajectories [59]; task duration and needle path [49]; accuracy, speed and trajectory [43]; “Follow the leader” [35]; target, reference points, planning time and distance between needle and tissues [33]; time and accuracy [27]; needle position [68]; trajectory and execution time [177]; depth of needle insertion, depth error from target criterion, rotating, lifting, and thrusting time, time error from target criteria and time ratio [95]. Some authors defined accuracy, for example, which consists of 4 measured parameters: distance from target to needle tip, distance from planned path to needle tip, distance from midline to needle tip, and distance from the anterior one-third of the vertebral body to needle tip [61]. Specifically for trajectories, the included studies applied certain techniques to assist in the training: Pareto principle to calculate optimal trajectory [45]; recommendation of trajectory [36]; trajectory defined by expert [110]; Record and Playback [177]; and recorded paths [49].

In certain procedures, such as biopsies (for prostate, breast and liver), brachytherapy and anesthesia, placement accuracy in millimeters is required. In the case of brain, fetus and eye procedures placement accuracy in micro-millimeters is desirable [129]. However, clinical studies have shown that targeting error (needle misplacement) may be due to imaging limitations, image misalignments, target uncertainty (patient motion, physiological or geometry related problems), human error (poor techniques and insufficient skills), target movement because of tissue deformation and needle deflection [129].

Other causes of inaccuracy in percutaneous procedures are physiological changes in the tissue during the time between the planning and treatment phases, glandular swelling during the procedure, difference in tissue type in each procedure, differences in the mechanical properties of healthy and diseased tissue, changes of mechanical properties when tissue is damaged and variability of soft tissue properties from the same organ in different patients [129].

Performance metrics differ from perceptual objective metrics because the latter aims at creating techniques to evaluate the quality of haptic signals based on user perception [178–181], applying psychophysical experiments. The creation of perceptual objective metrics can be explored to identify user perception, applying Just Noticeable Difference (JND).

7.2. Subjective tests

We observed a predominance of subjective tests, especially the questionnaires, including answers based on Likert scales (4, 5, 6, 7 and 10 items). The specific questionnaires were: NASA TLX (National Aeronautics and Space Administration Task Load Index Assessment) [76], ASQ – IBM (After-Scenario Questionnaire – International Business Machines) [160] and Bibliographic Collection and Usability Scale System with 16 items of satisfaction [85]. The NASA TLX questionnaire was related to robot-assisted surgery cognitive task load and was applied with Global Evaluative Assessment of Robotic Skills (GEARS) score (depth perception, bimanual dexterity, efficiency, autonomy, force sensitivity and robotic control); objective urethrovesical anastomosis (UVA) evaluation score (needle positioning, needle driving, suture placement and tissue manipulation). In this project, a sequential, modular criterion-based structured curriculum (Fundamental Skills of Robotic Surgery) for acquiring the basic skills of robot-assisted surgery was also analyzed [76].

Perception of visual or haptic sensations is a personal experience for each user. Thus, establishing verification mechanisms to create these questionnaires is still an unexplored point, which could be enriched by research in the fields of Psychology, Cognitive Sciences and Human-Computer Interaction, since in these areas the techniques are now more established.

The development of psychophysical tests is a promising field of study, since only two studies considered tests of this type: PSE (Point of Subjective Equality) and PMRE (Point of Motor Response Equality) [81,86]. We did not find measurement factors for Quality of Experience (QoE) [182].

Subjective analysis prevails, which opens opportunities for more complex objective analysis. However, it is necessary to devise specific tests to prove that skills have been transferred as a result of needle insertion simulations. Other ways to validate medical simulators are validity measurements [183], used in a small number of studies: face validity [10,26–28,59–61,80,103,121,184], construct validity [26,28,36,57], concurrent validity [76], predictive validity [26], content validity [27]; these same studies mentioned that the measurements would be applied in various future studies.

7.3. Number of participants and medical centers

We classified the studies into categories considering the number of participants in the tests: less than 10, from 10 to less than 20, from 20 to less than 30, from 30 to less than 40, from 40 to less than 50, and 50 and over, as well as studies that did not specify the number of participants. We also classified the studies according to the experience of the participants, defining two classes: experts and beginners. Beginners were residents and students at any stage of the course and who may have had some experience in performing the procedure. Experts were professionals or professors in the area.

Most of the tests involved a number of participants, from 10 to less than 20; most of the tests involving experts had less than 10 participants; and most of the tests involving beginners had from 10 to less than 20 participants. Beginners amounted to more than 50 participants in some studies [26,61,67], unlike experts, who exceed the range from 20 to less than 30 participants in one study only [26]. The number of participants in some experiments varied from one phase to another for various reasons (exclusion, withdrawal or primary calibration group), usually resulting in the diminution of these numbers [26,28,32,81]. There is no standardization concerning the minimum and maximum number of participants, experts or beginners, including the desired levels of experience of both classes of participants.

This review also analyzed the number of medical centers and the participant's work and study locations. This classification allowed the possibility for experts from different centers to perform certain procedures correctly, albeit in different manners, resulting in more than one training mode [5].

Most of the studies included considered one center only. The experiments performed in more than one medical center did not provide information to determine whether there were different ways to perform the same procedure. There were also formal tests with experts from different fields (computing and medicine) [37,124] and only a computing center [31,97,127,128].

7.4. Statistical tests and realism

In some experiments, but not all, the authors used tests that consider significant statistical differences among samples, such as ANOVA (Analysis of Variance) [30,32,33,36,56,67,86,107,157,185], Friedman [37,64] and Mann–Whitney U [28,31,67,176,186].

Finally, several studies included two types of realism (an important aspect in simulations), visual and haptic, associating these with two sensory modalities (visual and haptic). The auditory modality was explored in one study, but it was not evaluated [30]. Other sensorial modalities were not found (smell and taste). The degree of realism was mostly measured by using questionnaires.

8. Trends and challenges

We identified the trends and challenges for each category and divided into subsections. In addition, Fig. 2 presents some simulators found in the literature, with haptic devices.

8.1. Types of environment

Considering the types of environment, VR allows flexibility (anatomical variation and physiological replication) when compared to synthetic physical objects. TI has difficulties defining suitable materials to represent tissues and organs. In addition, it is difficult to prevent the wearing of these physical objects over time. In some situations, tissue wearing may be necessary, for example, when there are several needle-tissues contacts, that causes stress relaxation. This process must be simulated in VR and AR, in which environments are composed of virtual elements and simulation requires a high level of realism. AR can be an interesting approach, combining virtual and real elements to guide in a real spatial scale and prevent the wearing of tissues, although 3D registering is still a problem in the area. Although VR and AR are well-explored in the studies included, some ludic elements were carried out in the simulators. For example, the term "gamification" was found in some studies. In this context, the use of game concepts in needle insertion could be an interesting research field.

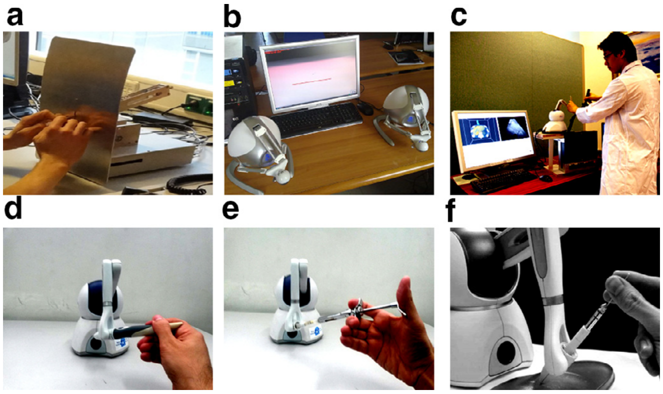

Fig. 2. Simulators and haptic devices – (a) specific – epidural anesthesia [28]; (b) two identical Novint Falcon for suturing [35]; (c) different devices for simulating VR ultrasound-guided biopsy [88]; (d) phantom Omni; (e) modified Phantom Omni for dental anesthesia [120]; (f) modified Phantom Omni for Chinese Acupuncture [187].

Also with relation to environments, a formal comparison between VR and AR systems for the same procedure could be important to determine advantages and disadvantages. We found only one comparison of this kind, and other comparisons involved VR/AR and TIs or ex vivo animals. Additionally, a 3D object to represent the user's hand or arm could be an alternative in order to reach user immersion in VR environments. This was not thoroughly explored, since the only objects handled by users in the environments were needles and syringes.

In the Software Engineering area, there was no reference to software testing for computational systems with haptic interfaces, so there could be an opportunity for a study field about software engineering. Simulators are complex systems, usually including one or more devices, different types of visualization, and robust algorithms to calculate the feedback. Thus, tools to automate the software testing activity can contribute to build higher quality systems.

With respect to collaborative systems, few works applied this training approach, but it would be interesting to do so, since students can learn by simultaneously executing the task with the instructor – while the instructor could perform student assessment during the training session. These systems usually require more than one haptic device, increasing the cost and complexity of developing the simulator (network technology, synchronization), and the presence of the instructor in all the sessions. However, offline approaches could help several students with minimum participation of instructors or only allow the use of a haptic device, which could prevent problems related to network technologies. For example, the record and playback techniques could be applied, as was observed in the review.

The use of machine learning in the simulators can help experts and beginners to understand the situations and to discover patterns, motions, skills and behavior in order to improve simulators and training.

8.2. Devices

The devices have limitations, especially the commercial ones, which are widely used. However, they can be modified to reach satisfactory realism by replacing the device stylus with syringes or needles. The ergonomic aspect of the devices is still a limiting factor for realism, since syringes and needles do not have coupled arms, as most haptic devices do, therefore adding parts that do not exist in the real world, or resulting in differences when compared to real training. The user can handle the syringe taking into consideration the weight of the device arm, which again, does not exist in the real world. Thus, developing specific devices is a challenge to cutting edge research.

Also related to devices, some of them do not provide five DoFF, necessary for some needle insertion tasks, but the needle insertion task can be simplified or simpler actions of the insertion task can be chosen (like as motions in only one or two directions), depending on the desired training (skills required), which require a smaller number of DoFF. Although this practice was common in the papers included, especially due to the limitations of the devices, authors do not usually explain how these simplifications and choices can be made. Therefore, explaining what can be simplified or chosen with no damage to realism is a challenge to innovative research, and it requires the participation of medical experts. The admittance-based device development and analysis for simulating some procedures is a research opportunity.

8.3. *Medical applications*

There are several procedures and target body regions which involve, for example, different types of needles. This increases the difficulty to develop medical training systems, requiring more complex haptic feedback and deformation models and methods. Yet, needle properties are not taken into account, such as thickness and length, as well as the needle bevel, which is not well-explored. To represent the needle with realism, haptic models and methods could consider needle breakage in accident situations.

8.4. *Haptic feedback*

Some of the models found have drawbacks, however, interesting solutions are presented in the literature itself and must be tested. For example, there are Hunt–Crossley and LuGre models, that may replace Kelvin–Voigt and Coulomb models in certain situations. We perceived that these research areas have evolved, while seeking for realism and efficiency.

There is a tendency for FEM implementation, although it requires excessive computational resources. This method, based on physics, is more realistic when compared to others, for example, Mass-spring. In computation, cost-benefit aspects must be taken into account when choosing a method. FEM provides high accuracy, especially for modeling small linear elastic deformations, but it usually does not provide for real-time execution when objects have a large number of vertices – calculation is time consuming, and its accuracy is very much dependent on its inputs. Otherwise, simpler methods can provide real-time response, but they do not provide high accuracy. Mass-spring, for example, has a more reduced computational complexity than FEM and may work well in real-time, but its use in simulations does not provide realism either in visual or haptic feedback, thus providing limited accuracy.

Therefore, application developers which use accurate virtual objects with a large number of vertices, whose simulation does not require high haptic or visual realism should choose a simpler method to provide real-time response, such as Mass-spring or similar methods. Examples of these applications are simulations of procedures where the organ considered is too small (such as a cell procedure or biopsy procedure in a small part of the brain). Other examples are applications which require very high level of detail, also resulting in a large number of vertices, but the realism of the required feedback is secondary (such as AR applications that use objects reconstructed with details to be superimposed on a specific real patient in order to plan a surgery). Furthermore, in applications where realism is a complex requirement (such as anesthesia) a more complex computational method is recommended, such as FEM. However, the developer should consider not processing all the vertices of the objects if real-time response is necessary. FEM may be based on iterative algorithms which do not require pre-computed structures, operating in the region of interest (contact between tissue and needle) because it has low computational requirements. In this area, research endeavors continue searching for physical realism and real-time simulation.

Another important issue refers to how to compare different algorithms for the same objective, such as force feedback or deformation behavior. It is a difficult task, since the objects, procedures and other aspects are different for each simulator. Thus a benchmark database with standard 3D objects could be interesting (with different number of vertices, number and size of edges etc), ensuring the standardization of tests with models and methods in order to generate force and deforming tissues and needles. This database could help to define parameters, varying mechanical properties between healthy, damaged and diseased tissues.

In order to provide realism in the models and methods, nonlinearity, viscoelasticity, inhomogeneity and anisotropy features must be taken into account to calculate haptic feedback and to determine tissue and needle behavior. In addition, physiological aspects such as respiratory motion simulation during needle insertion have attracted research interest. These aspects increase the complexity of developing accurate models and methods.

Also related to models and methods to generate haptic feedback and deforming tissues and needles, it is important to highlight that haptic device mechanisms can result in different perceptions by the users when compared to real procedures, even if the physical parameters obtained from real tissues are used. Therefore, calibration of simulation parameters should be carried out by experts. Similarly, it is crucial to have methods to analyze the behavior of tissues that must be simulated with these parameters, considering these tissues as virtual objects, separately or together in the virtual environment. In some situations the tissues are composed of layers that are reached by the needle during insertion. In addition, capture devices usually follow a direction angle to obtain values from real tissues, and in a procedure the needles can be inserted at another angle, which could result in differences during the simulation. Although beyond the scope of this review, these topics are of interest and warrant further study. In addition, since most of the models cannot represent combinations of tissue types and needle geometries to represent the effect of crack formation during needle insertion, each tissue layer requires a specific set of parameters, usually obtained from experimental data. Thus, studies that consider fracture-based mechanical models are desired, in which the effects of needle geometry causes permanent changes at the membrane or cell level when it interacts with tissue properties, creating new surfaces or causing damage inside a tissue during the insertion.

Finally, although there is consensus in the analyzed literature that a haptic update rate of at least 1000 Hz is necessary to provide haptic sensation, different haptic update rates of less than 1000 Hz were found. Therefore, studies should be carried out to analyze suitable haptic rendering rates for an adequate haptic sensation, including types of procedures, since other values (lower than 1000 Hz) may be satisfactory. However, prediction algorithms, such as Kalman filter or based on other stochastic models can be useful to predict force feedback and needle position, thereby increasing update rates. This filter was applied in the haptic field, for example, to reduce haptic data traffic in networked teleoperation systems [188].

8.5. User validation

We observed that it is difficult to define experiments specifying the number and subcategories of participants (beginners, experts or both), number of medical centers, types of tests (objective, subjective or both), and statistical test types, because there are several procedures and requirements, such as simulating different anatomical structures and needles. As would be expected, in each test the number of experts considered is smaller than the number of beginners, and as novices usually are the target users and are also quite varied, both in behavior and skill, they must be evaluated. Psychophysical tests and QoE measure factors could be applied in the tests, as well as suitable questionnaires (used to evaluate realism), which could be created considering collaborative efforts with other areas, such as Psychology and Cognitive Sciences. Subjective and objective tests were combined in various experiments. Moreover, it is important to specify experiments to assess the acquisition of knowledge and skills in needle insertion simulation (cognitive and motor aspects). For example, it is necessary to check how users hold and move the haptic device stylus, because they hold it as if it were a pen rather than a syringe, probably due to the shape of the stylus.

In terms of learning, which is the main objective of simulators, an interesting subject-matter to study would be an analysis of the need to have a learning phase in the experiment in order to understand the environments and technologies involved, reviewing user behavior and the influence of the systems in the training when users have experience using them, since the technologies and environments must assist in the training.

Also with regard to the evaluation process, simulators that consider two or more different ways to perform the same procedure were not found, since these ways may vary among medical centers. Thus, it is still a challenge to build needle insertion simulators that allow training the same procedure in different ways.

Robotic telesurgery training is growing and the haptic feedback is important, however, the contact between physician and patient is not direct, requiring an analysis of the need for other skills and new training techniques.

The formulation of perceptual objective metrics to evaluate haptic signals is still a challenge and can help identify errors perceived by users during human-computer interaction. These metrics can be applied in several simulations, including needle insertion, to improve the quality of the interaction, because errors, e.g., position deviations in a trajectory, can be identified and corrected without affecting user perception during the training; as well as for developing the system. Finally, the application of validity measures is becoming a trend and realism is an important aspect, albeit difficult to be measured.

9. Conclusion

In fact, there are several studies in the literature that investigate haptic interfaces for needle insertion training in the healthcare area. Nevertheless, there are still several challenges to overcome. The focus of this review was to specify research gaps that can be explored, providing a contribution in haptic interaction.

With this review, which covers the period from 1995 to April 2018, we noted that environments based on VR and commercial haptic devices are the trend. Force feedback was the type of haptic feedback found in most of the studies and there are few efforts to develop tactile feedback.

Gamification is increasing in this field and human perception evaluations are little explored. Many medical procedures and target body regions are studied, showing the importance of needle insertion in medical applications. The haptic models and deformation methods are studied in order to achieve suitable realism and rendering frame rates, considering haptic, visual and auditory feedbacks together (this is little explored). Problems with virtual needles, such as breakage, can be considered in simulations. Subjective and objective tests are combined in various assessments, and the questionnaires are used in many cases.

Conflicts of interest

None.

Ethical approval

Not required.

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Appendix A. Tables of results – systematic review

Legend:

S = Subjective; **O** = Objective; **E** = Expert(s); **B** = Beginner(s); **P** = Participant(s) (expert(s) and/or beginner(s)); **M** = Medical center(s); **C** = Computing center(s); **? (question mark)** = Unspecified device(s), commercial device(s), participant(s), expert(s), beginner(s), medical center(s) and computing center(s).

Table 2
Systematic review – IEEE search database.

Cit.	Procedure	Region	Environm.	Device	Model	Method	Test	User
[189]	Vertebroplasty	Spine	TI	Artifact and capture	Cortical and cancellous (cut and clamping)	No	No	No
[40]	Dye injection in sentinel node exam	Breast	VR	Phantom Omni	Needle displacement and resistance data by tissue type	Cloth simulation - variation of Mass-spring	No	No
[57]	Percutaneous therapy	Kidney	VR	2 Phantom Omni	Using stiffness, friction and cutting in depth	No	O and S	9 E; 18 B; 1 M
[41]	Anesthesia	Inferior alveolar nerve	VR	Phantom Omni	No	No	No	No
[158]	Percutaneous nephrolithotomy	Kidney	VR	Phantom Omni	Using stiffness and damping coefficients	Mass-spring	O	1 E; 3 B; 1 M
[190]	Surgery	No	VR	Phantom Omni	Model of [132]	Mass-spring	No	No
[42]	Anesthesia	Spine	VR	Phantom Omni	Using stiffness force, friction force and cutting force	No	No	No
[191]	No	Spine	VR	Phantom Omni	Virtual fixture control	Mass-spring	No	No
[127]	No	No	No	Specific (vibrotactile sleeve) and Phantom Omni	No	No	O and S	13 P; 1 C
[128]	Brachytherapy	No	No	Specific (wristband), artifact and Phantom Premium 1.5	No	No	O	17 P; 1 C
[176]	Biopsy	No	VR and TI	Phantom Omni and artifact	No	Method of [138]	S	12 B; 1 M
[159]	Anesthesia	Local	VR and AR	? device	No	No	No	No
[174]	Biopsy	No	No	Specific and capture	Reflective bending moment	No	No	No
[153]	Biopsy and vessel puncture	Liver or vessel	VR	Phantom Premium 1.0	Friction, cutting and base force	ChainMail and Multigrid	No	No
[192]	Kyphoplasty	No	AR	Artifact and capture	No	No	No	No
[193]	Biopsy	Liver	VR	Phantom Omni	No	No	No	No
[59]	Cholangiography	Bile ducts	VR	Phantom Premium 1.5	Hooke's Law and Coulomb friction (stick-slip)	Non-linear Spring	S	16 B; 1 M
[97]	No	No	No	Omega 6, specific and artifact	No	No	O	20 P; 1 C
[29]	Biopsy	Lung	No	Specific	Needle bending stress	Mass-spring	No	No
[105]	Thoracostomy	Lung	No	Phantom Omni and Novint Falcon	No	No	No	No
[48]	No	No	No	Specific and capture	Friction and Bingham Model/square plate of area	No	No	No
[106]	Biopsy	Breast	VR	Phantom Omni	Needle displacement, total force (using elasticity and damping) and friction	Mass-spring	No	No
[90]	No	No	VR	Phantom Omni	Shape matching and Coulomb friction (stick-slip)	No	No	No
[47]	Vertebroplasty and Kyphoplasty	Spine	AR	Capture and 2 artifacts	Standard linear solid model and friction	No	No	No
[60]	Brachytherapy	Prostate	VR	Phantom Omni and Phantom Premium 1.5 or 2 Novint Falcon	Shaft flexure and friction, tip cutting and deflection due to bevel	FEM of [150]	S	? E; 1 M
[98]	Biopsy	Lung	No	Specific	Needle bending stress	No	No	No
[91]	Cell injection	Cell	VR	No	Kelvin–Voigt and St. Venant–Kirchhoff	Strain Mass FEM	No	No
[16]	Spinal Intervention	Spine	AR	Phantom Premium 1.5	Coulomb friction and standard beam deflection model	FEM of [150]	S	7 E; 3 B; 1 M
[120]	Anesthesia	Inferior alveolar nerve	VR	Phantom Omni	No	No	No	No
[44]	Laparoscopy	No	No	Specific	Force peak integral – knot tying phase	No	O and S	11 E; 21 B; 1 M
[125]	Vertebroplasty and Kyphoplasty	Spine	AR	Capture and 3 artifacts	Sum of cortical (stiffness) and cancellous (cutting and friction – Heaviside function)	No	No	No
[170]	Optometry	Eyes	AR	Phantom Omni	Friction	No	O and S	5 B; 1 M
[43]	Cell injection	Cell	VR	Phantom Omni	Laplace equation	No	No	No
[35]	Laparoscopy - Suture	No	VR	2 Novint Falcon or 2 Phantom Omni	Using mass, elasticity and damping	Mass-spring	No	No
[36]	Radiological intervention	No	VR	Phantom Premium 1.5	No	No	O	3 E; 18 B; 1 M

(*continued on next page*)

Table 2 (*continued*)

Cit.	Procedure	Region	Environm.	Device	Model	Method	Test	User
[92]	Surgery	No	VR	Specific	Model of [132] and Bingham plastic model	No	No	No
[28]	Anesthesia	Spine	VR	Specific	Hooke's Law	No	O and S	1 E; 8 B; 1 M
[107]	No	No	TI	Artifact and capture	No	No	S	7 E; 21 B; 1 M
[10]	Anesthesia	Inguinal Region	VR	2 Phantom Omni	Hooke's Law and Karnopp friction	FEM	S	17 E; 23 B; 1 M
[194]	Surgery	No	No	Commercial: Simendo, Specific: TrEndo	Friction	No	No	No
[93]	Cell injection	Cell	VR	No	St. Venant-Kirchhoff	FEM	No	No
[99]	Spinal Intervention	Spine	AR	Phantom Premium 1.5	Standard beam deflection method and friction	FEM of [150]	No	No
[62]	Brachytherapy	Prostate	VR	2 Novint Falcon or Phantom Premium 1.5	Needle flexibility, lateral needle bevel forces, cutting and friction (stick-slip)	FEM of [150]	No	No
[63]	Brachytherapy	Prostate	VR	2 Novint Falcon or Phantom Premium 1.5	Shaft-aligned component (friction and cutting) and needle flexibility	FEM	No	No
[80]	Radiological intervention	No	AR	2 Novint Falcon or Phantom Omni	Gravity compensatory force	No	S	7 E; 1 M
[81]	Telesurgery	No	VR	Phantom Premium 1.5	Model of [132]	No	O and S	21 P; 2 M
[64]	Biopsy	No	VR	Phantom Omni and Phantom Premium 1.5	Variation of Voigt [131]	No	O	4 E; 12 B; 1 M
[172]	No	No	No	? device	Coulomb friction and cutting force	FEM	No	No
[83]	Cell injection	Heart	VR	Phantom Omni	Hooke's Law, static and dynamic friction and dynamic motion	No	O	10 P; 1 M
[195]	No	No	No	Capture	Kelvin	No	No	No
[163]	Surgery	No	VR	2 Phantom Omni	Euler-Topology	No	No	No
[136]	Cell injection	Cell	VR	No	Kelvin-Voigt and Euler Beam-Column	Mass-Tensor FEM	No	No
[94]	Cell injection	Cell	VR	No	Dynamic law of motion, Hooke's Law, Kelvin-Voigt and Euler Beam-Column	Mass-Tensor FEM	No	No
[52]	Anesthesia	Spine	TI	Artifact	No	No	No	No
[122]	Microsurgery	Blood Vessel	VR	Phantom Desktop[a]	Newtons Law, stretching, compressing, bending and twisting and the effect of gravity	No	No	No
[113]	No	No	No	Phantom Premium 1.5	Hooke's Law and Euler Beam-Column for deflection and buckling of the needle	FEM	No	No
[171]	No	No	No	Delta	Euler Beam-Column	FEM	No	No
[114]	Suture	No	VR	Phantom Premium 1.5	Variation of Voigt	No	No	No
[152]	Brachytherapy	Prostate	No	Capture	No	FEM	No	No
[115]	Chinese acupuncture	No	VR	Phantom Desktop or Phantom Omni	Model of [131], static and dynamic (Coulomb) friction for skin and muscle, viscosity and needle velocity for adipose tissue and penalty-based method (linear spring) for bone	No	S	10 P; ? M
[166]	Surgery	Suture	VR	Virtual Laparoscopic Interface, Laparoscopic Impulse Engine (Immersion Corporation), Phantom Omni and Phantom Desktop	Tension from the suture, the surface resistance, cutting resistance of the tissue as it is pierced and the resistance of tissue being pulled	Mass-spring	No	No
[167]	Biopsy	No	VR	? commercial	Hooke's Law	FEM	No	No
[75]	Biopsy	No	VR	Delta	No	No	S	1 E; 1 M
[118]	Microsurgery	No	VR	Delta	No	Multi scale FEM	No	No
[117]	Brachytherapy	Prostate	VR	Phantom Premium 1.5	Model of [196]	Restricted 3D ChainMail	No	No
[104]	Neurosurgery	Brain	VR	? commercial	No	Mass-spring	No	No
[123]	Amniocentese	Abdomen	AR	Phantom Premium and artifact	Needle force	FEM	S	20 E; 1 M
[197]	Laparoscopy	No	No	No	Force propagation	No	No	No
[53]	Anesthesia	Spine	VR	1D Impulse Engine	Look up table based on the depth of the needle penetration	No	S	? P; 1 M

[a] Currently Geomagic Touch X.

Table 3
Systematic Review–ACM Search Database.

Cit.	Procedure	Region	Environm.	Device	Model	Method	Test	User
[178]	Anesthesia	Alveolar inferior nerve	VR	Phantom Omni	No	No	S	14 E; 4 B; 1 M
[31]	Biopsy	No	VR	Phantom Omni and artifact	Based on a pig liver and constant speed	No	S	12 B; 1 C
[49]	Surgery	Spine	AR	2 artifacts	No	No	No	No
[148]	No	No	VR	Quanser 3DOF	Equation of nodal displacement, global mass, damping and stiffness	FEM	No	No
[46]	Surgery	Eyes	No	No	No	No	No	No
[34]	Optometry	Eyes	AR	Phantom Omni	Using parameters of viscosity, tension and friction	No	O and S	5 B; 1 M
[79]	Biopsy	Arm/Vessel	VR	Phantom Omni	Using elasticity/displacement inside tissue and damping (friction)	Mass-spring	S	? P; 1 M
[30]	Intravenous injection	Blood vessel	AR	Specific	No	No	O	60 B; 1 M
[198]	Intravenous injection	Antecubital basilica vein	TI	Specific	Using elasticity and friction cone	No	S	1 E; 1 M
[161]	Laparoscopy	No	VR	Phantom Omni	Cosserat Theory	FEM	No	No
[108]	Cell injection	Cell	VR	2 Cyberforce	Static and dynamic friction, using mass and stiffness/elasticity	No	S	3 E; 1 M
[84]	No	No	No	Phantom Premium 3.0	Incremental Voigt element and Coulomb friction [130]	Mass-spring	No	No
[65]	Radiological intervention	No	AR	Artifact	No	No	O	8 E; 8 B; 1 M
[149]	No	No	VR	Quanser 3DOF	Equation of nodal displacement, global mass, damping and stiffness	FEM	No	No
[33]	Biopsy	No	VR	2 Virtuose 6D Desktop	No	No	O and S	60 B; 2 M
[101]	Biopsy	Breast	VR	Phantom Omni	No	No	S	1 E; 11 B; 1 M
[51]	No	Prostate	VR	Artifact	Compensatory stretching force, bending and twisting forces for needle, Piola-Kirchhoff stress and static and dynamic friction (stick-slip) for tissues	FEM of [151]	No	No
[124]	Biopsy	Thyroid	VR	Phantom Omni	Model of [132]	No	S	? P; 1 M; 1 C
[85]	Anesthesia	Local	VR	No	No	No	S	13 E; 1 M
[86]	No	No	No	No	No	No	S	? P; 1 M
[164]	Suture	No	VR	Phantom Desktop and Phantom Premium 1.0	No	FEM	No	No
[102]	Biopsy	Blood vessel	VR	Phantom Omni	No	No	S	7 B; 1 M
[165]	No	No	VR	? device	No	No	No	No
[116]	Chinese Acupuncture	No	VR	Phantom Desktop	Variation of Voigt [131], weight compensation force, Hooke's Law and dynamic Coulomb friction	No	No	No
[168]	Surgery	No	No	? device	No	Mass-Spring and Enhanced ChainMail	No	No

Table 4
Systematic Review – Scopus Search Database.

Cit.	Procedure	Region	Environm.	Device	Model	Method	Test	User
[186]	Laparoscopy - Suture	No	VR	Box Trainer and Simbionix LAP Mentor (Simbionix USA)	No	No	O and S	36 B; 1 M
[54]	Catheterization	Spine	TI	Artifact	No	No	O and S	52 B; 1 M
[39]	Epidural anesthesia	Spine	VR	Phantom Omni	Using stiffness, friction and cutting forces, and needle on each tissue in two stages: before and after the puncture	No	No	No
[156]	Laparoscopy – Suture	No	VR	2 Phantom Omni	Relation between constant and original and stretched lengths of the section of the suture thread	No	No	No
[56]	Central venous catheterization	Vein at the apex of the head	TI	Phantom Desktop	No	No	O and S	14 B; 1 M
[58]	Cell injection	Cell	VR	2 Phantom Omni	Kelvin-Voigt	Discrete element method	O and S	13 B; 1 M
[157]	Catheterization	Arm	TI	Commercial: Virtual Intravenous Simulator (Laerdal Corporation)	No	No	O	19 E; 161 B; 1 M
[55]	Aspiration cytoloy	Thyroid	TI	Artifact	No	No	O and S	10 E; 35 B; 1 M
[199]	Percutaneous transhepatic cholangio-drainage	Liver	VR	Phantom Premium 1.5	Cutting force threshold, friction and stiffness	No	No	No
[185]	Laparoscopy â;; Suture	No	TI	Artifact and capture	No	No	O	10 E; 1 M
[95]	Acupuncture	No	TI	Artifact	No	No	O and S	12 B; 1 M
[76]	Urethrovesical anastomosis	Uretha	AR	Commercial: VLoc DaVinci Surgical System	No	No	O and S	52 P; 3 M
[96]	Acupuncture	No	TI	Artifact	No	No	O and S	16 P; 1 M
[32]	Biopsy	No	VR	2 Virtuose 6D Desktop	No	Method of [138]	S	1 E; 61 B; 2 M
[77]	Lumbar puncture	Spine	VR	2 Phantom Desktop	Needle tip, Karnopp friction and using clamping	No	S	20 E; 2 M
[155]	Biopsy	No	VR	No	Hooke's Law	No	No	No
[45]	Catheterization	Skin	VR	Phantom Premium 1.5 High-Force	Hooke's Law	No	No	No
[26]	Angiography	No	AR	Phantom Omni	Friction	B-Spline [73]	O	74 E; 52 P; 6 M
[61]	Spinal neurosurgery	Spine	AR	Commercial: Immersive Touch	No	No	O	63 B; 1 M
[160]	No	No	VR	2 Phantom Omni	Constant friction, Newtonâ;;s Law, using stiffness/elasticity and damping	Mass-spring	S	3 P; 1 M
[50]	Biopsy	No	AR	Artifact	Using stiffness/elasticity, Karnopp friction and cutting (force average)	No	No	No
[121]	Radiological intervention	Femoral artery	AR	Phantom Omni	No	No	No	No
[82]	Cell Injection	Cell	VR	2 Cyberforce Gloves	Static and dynamic friction, using stiffness (elasticity) and mass	No	S	5 E; 1 M
[133]	Regional anesthesia	Local	VR	2 Phantom Omni	Shaft friction and surface correction, model of [132]	No	No	No

(*continued on next page*)

Table 4 (*continued*)

Cit.	Procedure	Region	Environm.	Device	Model	Method	Test	User
[66]	Biopsy	Prostate	VR	Phantom Omni	No	No	No	No
[27]	Biopsy	Prostate	VR	Specific	Pre-pucnture, friction and cutting	No	O and S	14 E; 12 B; 1 M
[67]	Biopsy	No	VR	2 Virtuose 6D Desktop	No	No	O and S	60 B; 1 M
[184]	Injection of fluid and biopsy	No	VR	Phantom Omni, Desktop, Premium 1.5 and Novint Falcon	Compensatory gravity	No	O	20 P; 1 M
[200]	Anesthesia	Local	VR	No	No	No	No	No
[68]	Brachytherapy	Prostate	VR	Novint Falcon	Needle flexibility, lateral needle bevel and friction	FEM of [150]	No	No
[37]	Surgery	No	VR	Phantom Premium 1.5 and Phantom Omni	Model of [130] (Voigt, friction and Newton's Law)	Mass-spring	O	10 P; 2 M
[162]	No	No	VR	2 Phantom Omni	No	Spline	No	No
[109]	Lumbar and ascites puncture	Lumbar and peritoneal cavity	VR	Phantom Premium 1.5	Hooke's Law and friction	No	No	No
[110]	Lumbar and ascites puncture	Lumbar and peritoneal cavity	VR	Phantom Premium 1.5	Hooke's Law and friction	No	O and S	55 B; 1 M
[69]	Biopsy	Prostate	VR	Phantom Omni	Hooke's Law and friction	No	S	3 E; 1 M
[111]	Biopsy	Lumbar	VR	Phantom Premium 1.5	Hooke's Law and friction	No	S	42 P; 1 M
[103]	Radiological intervention	Blood vessel	VR	2 specific	Bending Force	Mass-spring	S	? E; 1 M
[70]	Cholangiography	Liver	VR	No	Model of [139]	No	O	2 E; 1 M
[71]	Catheterization	Blood vessel	VR	2 Phantom Omni	Tissue resistance, pathology and physiological pulsation in needle puncture	No	No	No
[72]	Biopsy	No	VR	Phantom Omni and Phantom Premium 1.5	Variation of Voigt of[131], friction, cutting and needle path constraint	No	S	2 E; 12 B; 1 M
[73]	Radiological intervention	No	VR	2 Phantom Omni	Hooke's Law and tissue properties from look up table, gravity compensatory, friction parameters transition force between tissues and constraint perpendicular to the needle path	B-Spline	S	20 B; 1 M
[74]	Brachytherapy	Prostate	VR and AR	Capture	Voigt	Mass-spring	No	No
[177]	Laparoscopy	No	AR	Needle Driver (KARL STORZ Gmbh and Co. KG. Tuttlingen, Germany)	No	No	O	? P; ? M
[112]	Biopsy	Spine	VR	Phantom Premium 1.5	Penetrability, viscosity and friction, restricting rotation (spring) and transversal motion (quaternion)	No	S	? P; ? M
[38]	Vertebroplasty	Spine	VR	CyberGlove and Joystick	Beam model	FEM	No	No
[201]	No	Spine	No	Specific	Shaft force based on spring, viscous damping and torque	No	S	? P; ? M
[202]	No	No	No	Capture	Shaft force	FEM	No	No
[173]	No	No	VR	Capture	No	FEM	No	No
[203]	Biopsy	Spine	VR	? commercial	No	No	No	No
[169]	Anesthesia	Local	VR	? commercial	Hounsfield units	No	No	No
[100]	Anesthesia	Local	VR	? commercial	Look up table	No	No	No

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