Robotic Simulators for Tissue Examination Training With Multimodal Sensory Feedback

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***Abstract*—Tissue examination by hand remains an essential technique in clinical practice. The effective application depends on skills in sensorimotor coordination, mainly involving haptic, visual, and auditory feedback. The skills clinicians have to learn can be as subtle as regulating finger pressure with breathing, choosing palpation action, monitoring involuntary facial and vocal expressions in response to palpation, and using pain expressions both as a source of information and as a constraint on physical examination. Patient simulators can provide a safe learning platform to novice physicians before trying real patients. This paper reviews state-of-the-art medical simulators for the training for the first time with a consideration of providing multimodal feedback to learn as many manual examination techniques as possible. The study summarizes current advances in tissue examination training devices simulating different medical conditions and providing different types of feedback modalities. Opportunities with the development of pain expression, tissue modeling, actuation, and sensing are also analyzed to support the future design of effective tissue examination simulators.**

***Index Terms*—Medical training, tissue examination, robotic simulator, multimodal simulation.**

I. INTRODUCTION

THE growing population, the aging society, migration, and changing patterns of diseases pose challenges to training healthcare professionals for changing conditions [1]. Health is critical to human development, and we increasingly consider technologies as a key factor in facilitating the healthcare system. Advances in science, engineering, and manufacturing continuously provide new and effective solutions in disease diagnosis, medical treatment, and rehabilitation. The training of healthcare workers can also benefit from the new technologies with assisted training in both fundamental sensorimotor skills and complex techniques for innovative tools [2]. Medical procedures are particularly challenging when practitioners acquire multiple channels of information for immediate actions based on real-time decision making [4]. The training typically requires many years of hands-on experience, limits the growth of the number of skilled healthcare workers, and increases the rate of suboptimal experiences for patients if trainees repeatedly examine them [5]. Hence, there is an increase of interest in simulation-based education (SBE) to provide safe and effective training scenarios for the trainees to enhance their performance and reduce the risk of complications in patients [6]. Conventional medical training methods [7], such as theatre-type live demonstrations and engagement with real patients, are often limited by irregular accessibility, insufficient quantitative feedback, and the shortage of teaching resources [5]. In contrast, the emergence of medical simulators that enable advanced SBE offers a student-tailored training environment for the errors and mistakes to be tried out without liabilities [12]. With such a simulation-based approach, student performance can be evaluated and scored in a quantitative and controlled system. The medical trainers can develop further scientific learning methods based on the simulated scenarios, such as confronting the mistakes in quantitative debriefing and systematically criticizing the step-by-step protocol [12].

SBE can be enabled via a wide range of learning techniques, such as standardized patients (SPs, actors coached to portray a patient), screen-based virtual programs of realistic physiology, part-task trainers, electromechanical life-sized interactive manikins, and complex scenarios (including training in non-technical cognitive skills) [13]. It is difficult to simulate abnormal physiological conditions and symptoms for many SP-based clinical training tasks. Physical examination maneuvers are also limited as it would be too difficult and expensive to recruit well-trained SPs for specific tasks such as breast examination and pelvic examination [13]. It is also challenging to practice with particular demographic groups such as infants [14].

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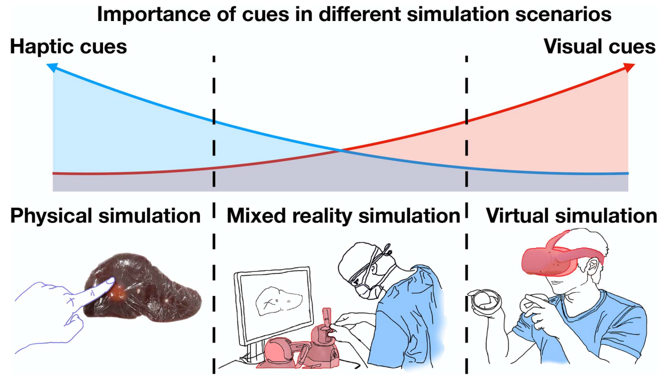

Fig. 1. Taxonomy of the physical-virtual simulation continuum with respect to sensory feedback. An example of a typical physical simulator is the organ phantom made of rubber [3]. In contrast, virtual simulation is the pure visual representation via a computer screen with the possible involvement of wearable goggles. Mixed reality simulators enable interactive training via physical components (e.g., a haptic device, a manikin) and virtual media (e.g., computer screen, VR glasses, AR projections). Visual feedback is generally more flexible and easier to simulate in a virtual simulation, while haptic feedback is more reliable and realistic in a physical simulation.

Robot-assisted simulation-based education (R-SBE), with an embraced integration of robotic simulators, is a more prudent method to provide a safe, diverse, and transparent training environment.

Following a common conception of virtual reality simulation, this paper modified the taxonomy from [15] to the design of medical simulators with further consideration of sensory feedback (Fig. 1). A physical simulator involves minimum virtual components with a focus on the sense of touch and anatomical appearance (e.g., the manikin patient simulator from Laerdal, see Fig. 2 a). On the contrary, a pure virtual simulator simulates only the visual cues of the clinical case. As tissue examination focuses on the hands-on operation and physical interaction, a pure virtual simulation system is rarely implemented. It is commonly used as the visual supplement with a haptic device to establish a virtual environment [16], [17], see Fig. 2 b. Such a visual-haptic feedback integration leads to a hybrid system of mixed reality simulation. Within such a spectrum of simulators, haptic feedback is easier to simulate with a physical system than a virtual one, while visual feedback shows an opposite trend in preferring a virtual system. It is necessary to notice that auditory and other augmented modalities are not considered in the physical-virtual continuum but are assumed to be independent.

Among the diverse fields of R-SBE, this paper focuses on medical simulators that are designed for tissue examination (palpation) training. Palpation is a widely-used clinical tissue examination skill medical professionals rely on. It involves a complex integration of haptic, visual, and auditory information underpinned by intricate coordination of sensorimotor skills and therapeutic attitudes [4]. During the procedure, a medical practitioner palpates the patient's body with their fingers and palms to detect certain characteristics of the tissue, such as the texture, stiffness, size, form, and tenderness [18], [19]. The practitioners are taught not only to look at the region they palpate but also look at the face of the patient to detect if there are facial expressions to hint the underlying conditions [4], [18]. A high level of multimodal sensorimotor coordination is demanded by the clinical tissue examination protocol. The technique is of particular interest in the field of R-SBE due to its high requirement in multimodal simulation, broad clinical applications, and the ability to generalize to other subjects of training [13].

Previous research shows that increasing the modalities of sensory input in a simulated environment can increase both the trainee's sense of presence and memory of the simulated tasks [33]. This paper analyzes current design solutions for medical simulators for tissue examination training, emphasizing multiple sensory feedback modalities. Sec. II summarizes the types of palpation and the common techniques regarding sensorimotor coordination. Sec. III categorizes the technologies that have been used in simulating multimodal haptic feedback simulation with commonly used methods to render kinesthetic and cutaneous cues. Sec. IV formats an overview of supporting sensory modalities in addition to haptics, including the simulation of visual and auditory feedback with the objective of increased realisticity or virtual augmentation. Finally, Sec. V discusses trends and opportunities for next-generation palpation training simulator design.

II. SYSTEMS AND APPLICATIONS OF PALPATION TRAINING

Palpation techniques vary with the aims of the examination or the area being examined, such as abdominal palpation or breast palpation [7]. The particular training focus and sensorimotor skills are also different. Common types of palpation, such as thoracic, abdominal, obstetric, uterine, hernial, breast, prostate, joint, and palpation used in open surgery, are listed in Table I, with key findings of sensory modalities categorized. The palpation task used in MIS is also included here, but it needs to be noted that such palpation is achieved via operation tools, and signals are processed via sensor/actuators, see Fig. 2 d. The visual and haptic cues are clearly differentiated in the table, while communicative cues such as tenderness are considered to be presented partly through auditory feedback, while they are also indicated via visual information such as facial expressions. By classifying the medical scenarios from the perspective of information channels, one can construct an interactive architecture to design the R-SBE systems that render the clinical cues.

Depending on the types of clinical cues the practitioners are looking for during the diagnosis, palpation techniques can also be considered as high-level tasks built on fundamental skills such as stiffness discrimination, texture recognition, shape evaluation, and tenderness evaluation [4], [7], [18]. When the practitioners examine the liver in abdominal palpation, they focus on stiffness discrimination and shape evaluation by detecting the organ's boundaries, often with a still hand feeling how the liver edge descends during inspiration [4]. In breast palpation, medics use stiffness discrimination of different types to diagnose if there are lumps [27]. In uterine and ovarian palpation, the medics use texture recognition to evaluate the organ smoothness, palpate organs between two hands (one external and one internal) [25]. In joint palpation and obstetric palpation, the practitioners are mainly looking for the geometry information to evaluate the

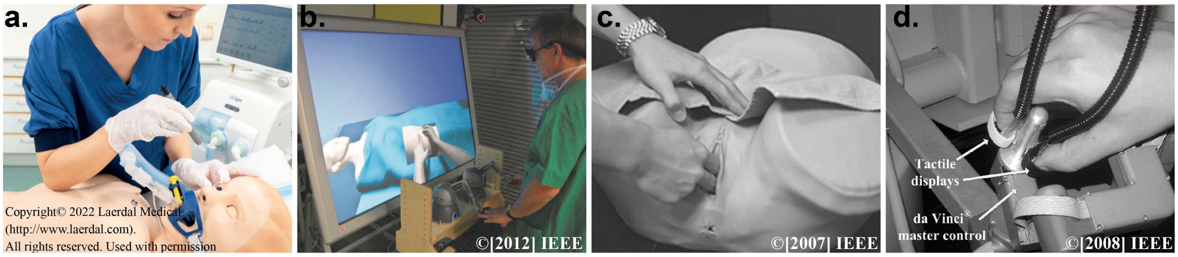

Fig. 2. (a) A commercially available patient simulator that provides visual feedback of the anatomy, a certain level of haptic feedback, auditory feedback of cardiac sounds, breathing sounds, and pre-recorded patient voice [8]. (b) A virtual training platform with integrated visual feedback of the clinical environment and haptic feedback via a pair of haptic devices [9]. (c) A pelvic examination simulator with embedded sensors for supervised palpation training [10]. (d) Tactile display arrays mounted on the master control tool of the da Vinci surgical system to provide feedback in minimally invasive surgery (MIS) palpation [11].

TABLE I
TYPES OF PALPATION AND SENSORY CUES

Type of palpation	Organs	Visual cues	Haptic cues	Auditory cues
thoracic palpation [20]	chest; spine; heart	facial expression; physical signs (spider hemangiomas); assessment of ventilation (symmetry, synchrony, and volume of each breath);	position of the vertebra; nodules; protrusion in the ribs, sternum, or spinal column; cardiac impulse/abnormal vibrations; ribs movement;	vocal fremitus; indication of pain (tenderness)
abdominal palpation [21]	abdomen; liver; spleen; kidney	facial expression; tissue deformation; breathing pattern [22]	stiffness; mass; texture; firmness; nodules; position; dullness; rigidity; guarding	indication of pain (tenderness and rebound tenderness) [23]
obstetric palpation [24]	abdomen; fetus	facial expression; fetal movement; skin conditions; fundal height	guarding; fetal lie; fetal presentation; liquor volume; fetal engagement	indication of pain (tenderness, verbal responses)
uterine palpation [18]	cervix; uterus; adnexa	Inspection for discharge or blood [25]	uterus size, shape, smoothness, clots, mobility and firmness	indication of pain (adnexal tenderness, cervical tenderness)
breast palpation [18], [26]	breast and nipples	discharge from the nipples; nipple retraction and redness [27]]	consistencies and lumps; elasticity of the nipples; temperature	indication of pain (focal swelling or fluctuance)
hernial palpation [28]	groin; scrotal	inspection for bulge or protrusion; inspection for scrotal masses	cough impulse, size, consistency, fluctuance, reducibility, composition; temperature	indication of pain (tenderness) [18]
prostate palpation [18], [29]	prostate		firmness, localized/generalized; bogginess and asymmetry; localized areas of softness, induration;	indication of pain (tenderness)
joint palpation [18], [30]	hand; wrist; knee; ankle; elbow; shoulder	anatomical landmarks; range of motion	subtle signs when moving such as crepitus (sensations); feel for fluid in joint; assess synovial membrane thickness; musculo-tendon junctions and tendon insertions for evulsion, tear and bursitis	subtle signs when moving such as crepitus (cracking sounds); patients express verbally about increased warmth, swelling, and focal areas of tenderness indicative of inflammation.
manual surgical palpation [31]	internal organs	appearance of the organ/tissue	tissue properties: stiffness, size, texture; the position of arteries; arterial pulse	
robotic surgical palpation [32]	internal organs (MIS)	endoscopy camera view	operational feedback or augmented haptic feedback of the organ through the device	

shape of either the bone or the fetus [30]. In most palpation techniques, medics evaluate the tenderness by looking at the patient facial expression, feeling of the patient tenses, or asking the level of pain [4]. When training with SPs, students can get direct feedback from the patients [38]. Although [39] and [40] reported that using simulators significantly improves the comfort level of medical students, those who learned on the simulator have mentioned that less feedback was received. Such a limitation can be overcome by designing multimodal robotic simulators to replicate various modalities in haptic, visual, and auditory formats, which can be found in real patient examination scenarios. In Table I, modalities in haptic are concluded from force, position, stiffness, texture, shape of the organ. Visual modalities include tissue deformation, the appearance of the organs, and facial expressions. Auditory formats include verbal messages, breathing sounds, or a break in the rhythm of breathing, and non-verbal phonation.

Another key advantage for robotic simulators is the anatomical variation [38]. The study in [39] reported that there are significant differences in the examination techniques used by clinicians based on patient factors. In contrast to using SPs in the training process that only has very limited variations in demonstrated pathological cases, R-SBE shows the advantage of simulating abnormal variations.

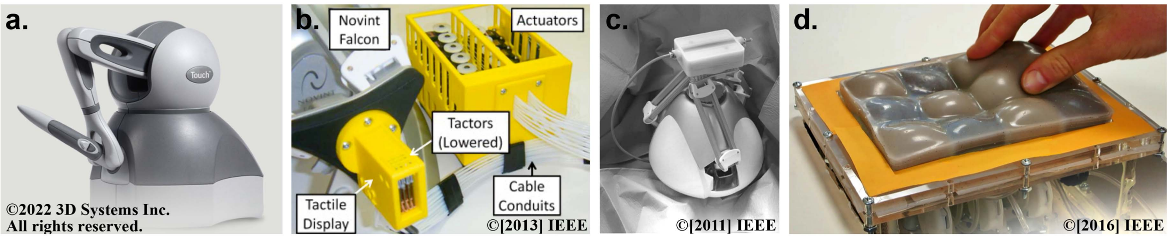

Fig. 3. (a) a Touch Haptic device, 3D systems [34]. (b) a pin array tactile display [35]. (c) Modified Novint Falcon haptic device with a mounted tactile display [65]. (d) A configurable physical display achieved with granular jamming [37].

III. MULTIMODAL HAPTIC SIMULATION IN PALPATION TRAINING

Haptic feedback is undoubtedly the most critical part of a tissue examination training simulator. In the context of design, haptic simulation aims to provide haptic feedback via interfaces that render cues related to human touch on fingers and hands [41]. Haptic rendering is commonly divided into two subcategories: kinesthetic and cutaneous [42]. Kinesthetic sense refers to large-scale force, motion, and configuration information felt at the tendons and spindles. This is related to both proprioception of the body itself and exteroception when we interact with the environment [43]. For example, kinesthetic sense includes the notation of configuration and location of the body in space and how much force one applied to an object. By contrast, cutaneous sense, also known as tactile sense, relies on the mechanoreceptors underneath the skin to detect features like temperature, texture, slippage, vibration, and low-level force that one can just feel on the skin [43].

In this regard, two major groups of artificial haptic interfaces are developed to present the aforementioned two modalities, namely, haptic devices and tactile displays [32], [42]. A typical kinesthetic simulator is a haptic device that mediates limited contact point interaction between the computer and the users. Such a type of device tracked a user's physical input with integrated sensors and provided force/position simulation (e.g., PHANTOM haptic device, see Fig. 3 a). A tactile display that focuses on providing stimuli to the user's fingertip is a typical cutaneous simulator while no kinesthetic sense has resembled in the simulation (e.g., tactile pin array for fingertip, see Fig. 3 b) [35]. The technologies of the two groups of haptic interfaces and their applications in palpation training are further discussed in-depth in Subsec. III-A and Subsec.III-B. Most of the palpation tasks, such as abdominal palpation, rely on both the integration of kinesthetic and cutaneous sense [44]. Thus, this poses a need to develop an additional type of artificial haptic interface that provides realistic and transparent haptic interaction in both kinesthetic and cutaneous senses. We categorize two solutions by looking through palpation simulators developed in the last thirty years. Firstly, miniaturize the tactile display and mount it on a haptic device as the new end-effector (see Fig. 3 c). Secondly, find solutions in material science and mechatronics to develop a configurable physical interface (see Fig. 3 d). The latter case can also be called a soft robot that can be programmed to enable different physical haptic interactions. Since the configurable physical interface simulates the scenario in the physical environment, both kinesthetic and cutaneous sense can be provided. The development of the two solutions and their applications in palpation training are addressed in Subsec. III-C and Subsec. III-D. Table II summarizes key studies of robotic simulators for palpation training in a chronological order. The details about the control/programming architecture for the cited devices are not discussed yet can be found in the referenced publications.

A. Haptic Devices for Kinesthetic Feedback

Haptic devices are the most commonly used haptic interface in currently developed palpation training systems. Although there are many definitions of "haptic device," the most well-accepted version describes the term as a mechanical device that enables kinesthetic interaction between human users and the computer [65], [88]. Haptic devices can be designed in different manners. This survey categorizes five large groups of haptic devices that can be used for intuitive palpation training: desktop manipulandum, exoskeletons, wearables/gloves, grippers, and pneumatic cylinders.

Desktop manipulandum has been one of the only commercially available types of haptic devices for the last 30 years. It has the advantages of high precision, ease of control, high-frequency bandwidth, and ease of being implemented in a diverse virtual environment. However, such devices normally only render a single point of interaction up to 7 degrees of freedom (DoF). The limits in workspace and dexterity pose a challenge in manual palpation training, typically requiring more diverse interaction. Common models used in palpation simulator designs include the Phantom series (Omni, premium, 1.5, etc.), Novint Falcon, and Haption Virtuose desktop. For programming and control these commercially available haptic devices and rendering a virtual interactive model, supporting packages include, GHOST haptic library [16], [49], [56], Magma [17], CHAI3D [58], [71], H3D [60], HDAPI [73]. A detailed technical comparison of the commercially available haptic devices can be found in [65], where a list of the companies, devices, and capabilities is provided.

Exoskeletons are devices directly attached to the human body (the hand in most of the palpation simulators) to provide constrained kinesthetic feedback in force and compliance. A typical exoskeleton device used in palpation training is the 5-finger haptic interface robot (HIRO), where kinesthetic feedback of the virtual tissue can be provided to the fingers [53]. Exoskeletons can be either stationary (fixed on the ground or environment) or mobile (move with the human body, not fix to the environment). When such devices are fully mobile and worn by the user, the device can be called wearables/gloves. For instance, an early

TABLE II
HAPTIC SIMULATION FOR KINESTHETIC AND CUTANEOUS FEEDBACK USED IN VARIOUS PALPATION TRAINING METHODS/SIMULATORS

Year	Palpation training system	Kinesthetic feedback	Cutaneous feedback	Specifications
1994	knee palpation simulator [45]	DataGlove and Rutgers Master [46]		4N per finger; 8-10Hz simulation rate
1997	abdominal palpation liver tumor detection† [47]	Rutgers Master II, A Polhemus FASTRAK 3D tracker		16.38N per finger; 14-15Hz simulation rate
1999	digital rectal examination†† [16]	Phantom arm*		GHOST haptic library; 3DOF; 10N; 1000Hz simulation rate
2001	head and neck [17]	Phantom desktop*		programming API/environment for the haptic device: Magma® (ReachIn Technologies AB, Sweden)
2003	cardiac surgery [48]	adapted Phantom*		1DOF(4cm) for the finger and 4DOF for the wrist
2003	human back [49]	two Phantom 3.0*		SensAble Technologies GHOST software; 22N; 0.02mm nominal resolution; 39x54x75cm workspace
2003	tissue stiffness simulation [50]	Stewart type platform with pneumatic cylinders	static soft breast silicone model	6DOF; minimum stiffness variation of 0.1[N/mm]
2003	breast palpation lump simulation†† [51]	silicone breast model with pneumatic controlled inflated lumps		15 controllable lumps
2004	liver palpation simulator for laparoscopic surgery† [41]	Phantom*		self-developed program written in VC++ with openGL; 6DOF; 8N; 1kHz
2004	tissue properties rendering [52]		haptic actuator array with electrorheological fluids	nearly 10N with a 1 cm2 piston head
2005	breast palpation simulation† [53]	Haptic Interface Robot (HIRO)		a 6DOF arm and a 3-finger haptic hand(3DOF each)
2005	rectal palpation †† [54]	Phantom Premium 1.0A*		300Hz refresh rate
2006	palpation simulator† [55]	Phantom Premium*	pin array tactile display	tactile display (6x8 pin array, 50x14x18 mm and less than 30g), 200Hz bandwidth and up to 0.5N; 1kHz simulation for the haptic device
2006	virtual palpation system [56]	Phantom DesktopTM*		GHOST SDK; simulation based on ultrasonic elasticity imaging
2008	a virtual breast patient†† [57]	a physical manikin with a breast simulator as the tangible interface provides passive haptic feedback and affords haptic input		contains twelve pressure sensors to detect the user's touch with passive haptic feedback provided
2009	femoral pulse palpation [58]	Novint's Falcon	piezoelectric pads; micro speakers; a pin array device [59]	CHAI3D 1.51 for haptic response; 3DOF for the haptic device; Piezoelectric Pads (¡1mm), zero to 300 pulses per minute; micro speaker, 7.5g with a diameter of 19mm; pin array, 4 by 4 remotely actuated pins with up to 1.3N force and 2mm displacement
2009	tube thoracostomy palpation simulator [60]	Phantom Omni*		H3D software virtual environment; finger casings with silicone-elastomer (driving with DC motors to provide constriction)
2009	cardiac muscle palpation [61]	"the Linear Slider"		1DOF feedback controlled linear slider with a spring system
2009	virginia prostate examination simulator†† [62]	physical prostate simulator with tunable stiffness tumors and embedded sensors		4-6 polyethylene balloons (hardness range of 0–35 Shore A durometers)
2009	colonoscopy abdominal palpation [63]	a pneumatic bladder to simulate the feel and flexibility of human tissue during palpation		a 9cm by 11cm two-valve sphyganometer bladder (0-8kPa); a delay of less than 230ms to follow recorded force; maximum force 85N
2010	breast palpation [64]	Phantom 1.5*	static silicone model	3DOF force feedback and 6DOF pose sensing; silicone model (Ecoflex 0030 and thinner)
2011	femoral palpation and needle insertion†† [65]	2 Novint Falcon	a custom built hydraulic interface to provide a pulse like tactile effect	5-force DOF haptic feedback (1,000 Hz, up to 14.15 N); tactile actuator specification not provided; only one Novint Falcon for needle insertion simulation
2011	clinical breast examination simulator [66]	a physical breast model		a sensing platform with a 5kg load cell (250 Hz); a boom-mounted camera for position tracking
2012	arterial pulse palpation †† [9]	Phantom Omni*	palpation pad; thimble(static)	a corotational FEM from SOFA for tissue property simulation; 3DOF movement; 3 mm thick foam rubber for the palpation pad
2012	lump display in MIS [67]		adjustable aperture air-jet pneumatic lump display	aperture size (1.9, 2.3, 2.8, 3.2, 3.8, 4.1, and 4.5 mm) was measured at each supply pressure level (10, 20, 30, and 40 psi)
2012	liver palpation simulator for laparoscopic surgery [79]	2 Phantom Omni*	a Maryland pense	the Maryland pense (Forceps) is attached to the haptic device and is restricted through a metal ring that simulates the trocar entry point.
2013	tactile surface display [37]	deformable geometry with positive air pressure; variable stiffness and texture with negative pressure granular jamming		3×4-cell prototype
2013	seldinger technique and angiography training†† [68]	Phantom Omni*	a manikin and the attached SimPulse provides a tangible interface that simulated pulse	additional workstation: a needle holder haptic device and a Vascular Simulation Platform (Gothenberg, Sweden)
2013	remote palpation lump localization† [32]	Novint's Falcon	remotely-actuated electromechanical pin array shape display [70]	4x4 pin array with a centre-centre separation of 2.5mm, displacement of 2.5mm, and 5N/mm stiffness; lateral displacement 3mm (200 um each step), stiffness 5N/mm, speed 40mm/s
2014	multi-finger Palpation with tumor simulation† [70]		granular jamming to simulate tumor in organ and pneumatic chamber for stiffness rendering	jamming actuation: -0.001 to -0.1 MPa; pneumatic chamber inflation: 0.01 to 0.1 MPa
2014	skin palpation simulation (dermatology) [71]	Phantom Omni*		CHAI3D libraries; 3DOF force feedback, 6μm position resolution, 3.3 N and 2.31 N/mm for max force and stiffness
2014	abdominal palpation training simulator [72]	control of flexible sheets		lower sheet (stretching to increase stiffness); upper sheet (breathing movement)

TABLE II
(CONTINUED)

2016	virtual abdomen model†† [73]	Phantom Premium 1.5*		OpenHaptics low-level API (HDAPI); 6DOF; nominal position resolution: 860 dpi translation; 0.0023 degrees for yaw and pitch rotation and 0.008 degrees for roll rotation. The translational force out-put is limited to 8.5 N peak and 1.4 N continuous. The maximum exertable torque is 515 mNm for yaw and pitch and 170 mNm for roll. The continuous exertable torques are 188 mNm and 48 mNm, respectively.
2016	tissue behavior [74]	pneumatic actuators		Airpel M16D100D with a 100mm stroke and maximum force of 110 N
2016	open-surgery simulation: artery pulse palpation†† [75]	physical simulation platform, silicone model	wearable haptic device (fabric yeilding)	up to 15mm indentation and 8N force
2017	3D haptic interface [76]	shape and rigidity changing 3D haptic device		an array of non-expandable balloons; stiffness is controlled by regulating the volume of air
2018	liver simulator for palpation [3]	silicone liver model with controllable positive granular jamming tumors		liver model fabricated with ecoflex 0010 and Slacker (1:1 ratio); double-layer balloon for tumour simulation with positive granular jamming for stiffness control
2018	virtual tissue palpation† [77]	magnetic levitation haptic device		an adjustable coil array consists of three current-carrying cylindrical coils to generate the effective magnetic field; real-time 3D positioning and tracking of the magnetic stylus accuracy (0.28mm)
2018	clinical breast examination simulator†† [78]	static breast model with underlying force sensor platform		44 × 44 matrix sensor platform (250 × 250mm, TekscanBoston, MA); 90hz
2018	prostate palpation simulator†† [80]	anatomy manikin with pneumatic controlled nodules		double-layer balloon: internal layer (granular jamming, stiffness control), external layer (blown effect, size control)
2019	ophthalmic anesthesia palpation training [81]	a manikin with embedded position sensor (soft-pots) and a load cell		soft-pots (membrane potentiometers, Spectra Symbol 391, 40x10mm, estimation error less than 0.85%).
2020	soft 3D haptic shape display [82]	shape and stiffness changing 3D haptic device		an inflatable silicone membrane with embedded particle jamming cells (stiffness control) and soft pneumatic actuators (shape control).
2020	hand bone protrusions palpation†† [83]	Virtuose 6D Desktop, Haption; 3D printed haptic phantom hand	3D printed haptic phantom hand	phantom hand 3D printed with stratasys printer (bone: VeroBlackPlus; tissue: a support-material (SUP) and TangoPlus filled metamaterial)
2020	sensorized abdominal phantom for palpation training [84]	multi-layer abdominal model with controllable organ with positive granular jamming tumors also as sensors to detect palpation force and trajectory		5 controlled nodules (controlled between 30-55 kPa stiffness) within the silicone liver, tissue, and skin model; testing trial with linear indentation palpation showed an RMSE of 4 mm (in the testing area around 100 × 100 mm) and 1.18 N (for the applied force up to 18 N) for the position and force estimation of palpation, respectively.
2021	haptic surface† [85]	tactile field with granular jamming of ferromagnetic granules to render shape, position, and hardness of palpable irregularities		260 x 160 mm; manipulated with permanent magnets
2021	haptic mouse† [86]	a mouse type haptic display for localized physical abdomen simulation and interaction to a virtual abdomen		different types of granular jamming and layer jamming mechanisms are tested to simulate the muscle guarding. granular jamming structures with soft, fine, and rigid granules, and layer jamming structures with stretchable and non-stretchable layers.
2021	robotic ankle-foot haptic simulator†† [87]	a physical robotic leg with movable ankle-foot mechanism		a hybrid of belt and linkage drive are used for the mechanism with an impedance controller. error: interaction torque from the trainee (average RMSE of 0.2 Nm) and closely track a chirp torque command up to 10 Hz (average RMSE of ¡0.22 Nm)
note:	*The Phantom series haptic device used in the above studies were the models developed and manufactured by Sensable Technologies. However, the brand is currently owned by 3D systems with new models as Touch, TouchX, and Premium [34]. † studies that involves human factor study. †† studies that involves human factor study with medical professionals (including objective feedback via surveys/questionnaires).			

glove-type development called Rutgers Master can simulated interaction compliance with pneumatic cylinders [45]. Both exoskeletons and wearables/gloves have few applications in palpation training with no inventions in the recent fifteen years. Part of the reason could be that such devices are relatively bulky and complicated as an early prototype. Palpation is a delicate and high-sensitive diagnostic technique where the practitioners perform with their bare hands. If the exoskeleton provides too much undesired constrain or friction due to mechanical design, both the haptic sensation and sensor-motor coordination can be affected. However, with the current development of soft robotics and light-weight wearables [89], wearables can play an important role in the next generation palpation simulator design with increased flexibility. More specifically, it has the potential to be merged with configurable physical interfaces to provide both kinesthetic and cutaneous feedback.

Grippers are special haptic devices that only simulate one or two degrees of freedom associated with human grasping or gripping motion. The implementation of this type of haptic device in palpation training is in shortage. A similar concept has been used in the da Vinci Surgical System's thimble design, where the users can feel a force about how much they are squeezing the object [90]. However, the thimble design only passively provides the squeezing resistance with a spring. By providing additional programmable interactive kinesthetic feedback to the gripping fingers, the gripper type of haptic device can be used in MIS palpation or manual palpation training that requires squeezing gestures such as thoracic palpation.

Finally, pneumatic cylinders have also been used as a haptic device to provide force feedback. Natural pneumatic compliance has proved to be a good interface to simulate compliance in soft tissue with complicated tissue dynamics. The system also has the advantages of high robustness and high simulated force range. However, the difficulty in controlling pneumatic cylinders limits their applications in current palpation simulator designs. Typical implementations of the pneumatic systems include the Stewart type platform used for breast palpation simulation [50], and the work by [74] that simulates tissue behavior.

B. Tactile Displays for Cutaneous Feeback

Fingertips, and more importantly, the sides of the fingertips, are critical during the haptic exploration process in tissue examination [91]. The material stiffness and texture of the object can be determined by evaluating the distributed pressure on the fingertip. Because the mechanoreceptor located underneath the fingertip is very sensitive to a range of mechanical features, designing robotic systems to selectively provide stimuli to the fingertip becomes an effective solution to simulate virtual cutaneous feedback. Tactile displays, also known as tactile devices, are developed following this concept. In this survey, we will follow the notation of tactile displays instead of tactile devices since most of the technologies introduced only provide tactile stimulation output without integrated tactile sensors that can measure the input. This is different from haptic devices as it enables both kinesthetic input/output (I/O).

In contrast to haptic devices, where desktop manipulandum dominates the medical simulator designs in the last thirty years, tactile displays are much more diverse. This survey categorizes the current tactile feedback display designs into three types: Movable stimuli array, non-physical stimuli, and variable stiffness material.

Movable stimuli array works in the concept of providing an array of pressure patterns to the fingertips of the users to present the sensations of 3D shapes, textures, and slippage [92]. Typical designs within this category are vibrating pin array, pneumatic balloon array, soft gel actuator pin array, and electrorheological fluids arrays [93]. Array-based simulation describes the relationship between a tactile display's matrix density and the human fingertip's recognition performance [94]. By programming the mechanical features of each unit in the array, different sensations can be illustrated [42]. The array-base mechanism to simulate cutaneous feedback has the advantages of ease of programming and simulating fine features. However, it usually requires sophisticated hardware for controlling the array and the difficulty of scaling up (with increased workspace) limits its use in tissue examination simulator design. In addition, human skin can distinguish very fine mechanical and geometrical features. It is challenging to produce an unnoticeable realistic feeling of touch when the user are doing active exploration with the fingers. This poses the most practical application of the tactile display in MIS palpation training with the integration of a commercial haptic device.

The non-physical stimuli type works on a similar principle to the movable stimuli array method, except the stimuli are non-physical. Instead, stimuli to the fingertip are provided by air-jet, ultrasonic and acoustic vibration, electrotactile stimulation, or vibrating voice coils [93]. Unlike an array of vibrating pins, the non-physical stimuli type of tactile display design is more flexible. Indeed, the control of the system can be more sophisticated. From the authors' knowledge, the implementation of such a tactile display in manual palpation training has not yet been well explored.

Finally, the development of variable stiffness material initiates the last type of tactile display, simulating the overall mechanical property of the object. Tunable stiffness mechanisms are normally used within the display to enable a variety of simulated stiffness and geometry. In contrast to movable stimuli array or non-physical stimuli that actively stimulate the mechanoreceptors in the fingertip, tactile displays based on variable stiffness material simulate the mechanical property regardless of human touch. The interaction is entirely passive, and what a human can sense also depends on human haptic exploration. Technologies like granular jamming, phase-change material, magneto-rheological (MR) fluid, stretching fabric, and air pockets can be used to design this type of tactile display [95].

C. Haptic Devices + Tactile Displays

Although some researchers have already proposed the idea of attaching a tactile display on a desktop haptic device to provide integrated modalities of kinesthetic and cutaneous feedback, the actual implementation of such a solution is still in its infancy [96]. Training palpation technique with a desktop haptic device in a virtual environment limits hand gestures and tactile feedback. To solve the issue, researchers initially tried to replace the off-shelf stylus (either a pen or an operational ball) with a new design that has similar properties to human skin or tissue [97]. More advanced solutions upgraded the end-effector to a tactile display where programmable cutaneous feedback can be simulated. [58] proposed the concept of implementing a tactile display that works on piezoelectric pads, micro speakers, and a pin array device on a Novint's Falcon haptic device for femoral pulse palpation training. In the design of a tube thoracostomy palpation simulator, [60] constructed a physical apparatus on a Phantom Omni to provide users with both point feedback and constriction on the finger. For achieving remote palpation lump localization, [69] remotely actuate an electromechanical pin array shape display on a Novint's Falcon. Some simpler solutions also work well with pulse palpation simulation with a display that generates a pulse-like tactile effect [65], [68].

D. Configurable Physical Device

This paper defined a new group of devices called Configurable Physical Device with a description of "A programmable soft physical object that can change its own mechanical/electrical properties to provide both kinesthetic and cutaneous feedback by touch." Such devices can refer to soft robotics or, more specifically, in the medical simulator field as the "robotic patient". In a more detailed level, this group can be divided into two levels: Configurable Physical Display, which does not integrate sensing, and Configurable Physical Interface, which integrates sensing.

A typical example of a configurable physical display would be the surface display proposed by [37] (Fig. 3 d), where a soft deformable geometry with variable stiffness can be programmed with the combination of positive and negative air pressure. A similar granular jamming idea for stiffness control of configurable objects can also be found in [82], which presents a soft 3-D object that can change its shape. The advantages of such a tunable stiffness material are inherited from the previously mentioned tactile displays. Due to its flexibility in scaling-up, the presentation of the entire physical object instead of a small region for the fingertip becomes possible. This solution poses great advantages in palpation simulator designs where a more interactive simulated environment is desired. This type of physical presentation also ultimately solves the problem of the high-simulation refresh rate. For a conventional tactile display or haptic device, the system normally needs to be operated in a very high frequency to provide realistic human haptic feedback. Literature reported that the minimum noticeable refresh rate lies within 300 to 600 Hz [98]. Such a high-frequency requirement causes challenges in many previously discussed haptic feedback solutions. By contrast, the configurable physical display has no limits on the simulation frequency since it works on a passive principle, where the simulated tissue dynamic relies on the actual material property. This makes the configurable physical device a practical yet robust solution for controllable organ designs for palpation training. [3] have implemented novel positive pressure granular jamming nodules in the design of a robotic liver with controllable tumors. [80] have proposed a prostate palpation simulator with negative pressure granular jamming nodules as tumors. The use of inflatable air pockets has also been applied in the Virginia Prostate Examination Simulator, where tunable stiffness prostate tumors are simulated [99].

An essential feature of the configurable physical interface is embedded sensing. Similar to haptic devices, the integrated sensors make the system flexible in creating interactive closed-loop virtual haptic rendering. The sensor and actuation integrated interface also allows quantitative supervised training, whereby the trainees' interactions with the simulator are recorded. For instance, in the abdominal palpation simulator proposed by [84], the palpation force on the liver tumors and palpation location can be simultaneously recorded. The Virginia Prostate Examination Simulator can also measure the applied pressure on the prostate tumors while presenting several diseased conditions. The data gathered from the trainee performance during the examination can be evaluated quantitatively as a score and used as a reference to provide further instructions.

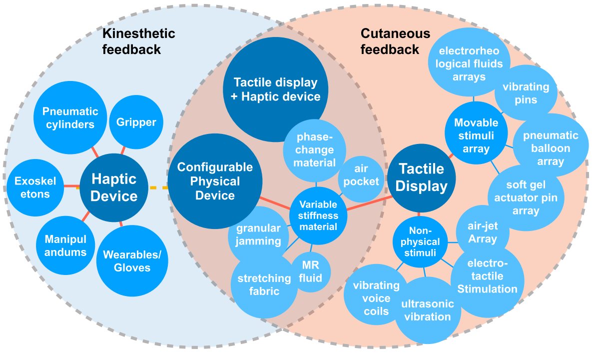

Fig. 4. Technologies used for multimodal haptic simulation in palpation training. The layout is mapped out for both kinesthetic and cutaneous feedback. Four major categories were defined based on existing research: haptic device, tactile display, configurable physical interface, and tactile display+haptic device.

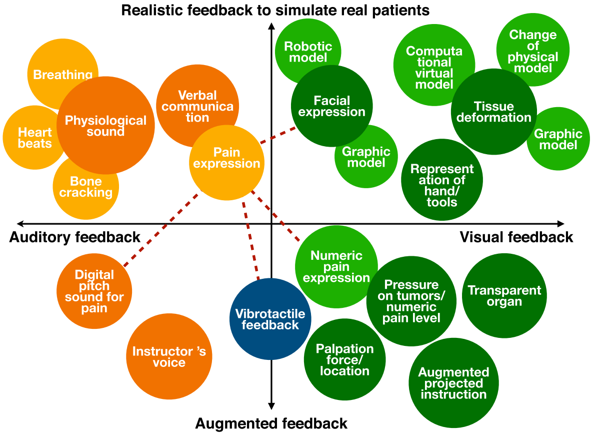

Fig. 5. A layout of objectives and technologies used for multimodal simulation for palpation training. The figure includes four quadrants while it represents the simulation with the objectives both in enhanced realisticity and augmented instruction based on visual and auditory rendering.

IV. Additional Supporting Modalities

Palpation training efficiency can be improved if the robotic simulator provides, along with haptics, other feedback modalities. [100] categorize six types of media to facilitate communication and learning: 1. Text, 2. Audio, 3. Visuals, 4. Video, 5. Manipulates (Objects), and 6. People. Many trainers and educators agree that computer technology transforms education more effectively compared to conventional methods. In addition to such an agreement, robotic simulators provide manipulation of objects and establish synchronization via providing text, audio, visual, and/or video effect.

A robotic simulator can present additional augmented modalities that are not presented when training with real patients, such as transparent organ locations, palpation instructions, and indicative force maps. These augmented modalities play an important role in the trainee's learning process to form a cross-validated reward scheme to master the skill quickly. This paper formulates the simulated features of robotic training systems in two domains depending on if a similar feature can be found in real patients. First, the term "realistic feedback to simulate real patients" is defined for the simulated features to resemble the realisticity of a real patient (e.g., facial expression, verbal communication). Second, "augmented feedback" is used to define features that are only presented in an artificial system (e.g., transparent organs, palpation force in a numeric format). Considering visual, auditory, and vibrotactile feedback to support previously discussed multimodal haptic simulation, as illustrated in Fig. 5, we grouped several classical feedback features in the scope of realistic feedback and augmented feedback.

A. Enhanced Realisticity With Multimodal Rendering

In physical examination, the diagnosis starts with the practitioners reviewing the patient's medical record, observing the appearance of the examed area, and listening to any informative sounds. In particular, how those multimodal cues change when the practitioners palpate on the patients. Replicating such a multimodal system is one of the fundamental goals of

Simulation-based training. On the one hand, palpation simulators providing visual and auditory cues rather than just haptics would help create a more realistic simulated environment with higher fidelity. On the other hand, adopting multiple channels of correlated sensory information would significantly increase the participant's awareness of the tasks. In this regard, three classical objectives can be categorized for the enhancement of simulation realisticity: tissue deformation, representation of hand/tools, and physiological sounds.

1) Tissue Deformation: In medical training, the degree of deformation on the soft tissue provides valuable visual information to trainees, helping them learn how to condition their behavior to achieve tasks effectively [101]. Estimating tissue deformation and its effects on the patients, e.g., inflicting pain, are key skills that require many years of experience. Providing an accurate prediction of tissue deformation to trainees, e.g., through virtual reality visualization, will help them rapidly improve their perception and behavioral conditioning skills because it allows them to observe how their touch affects the behavior of the tissue internally.

Virtual modeling in medical training aims to predict the relationship between hand/tool motion and tissue deformation. It requires mathematically modeling the anatomy and nonlinear response of various tissues and fingers. However, adding more details to the mathematical model leads to longer simulations time when solving the equations. As with simulating any other complex system, there is a trade-off between the resolution of the solution (in other words, degrees of freedom of the model) and computational costs. Two main approaches have been adopted favoring low cost or high resolution, lumped-parameters modeling, and computational modeling. A recent review article gives a well-structured overview of the real-time modeling approaches [102]. Existing surveys on soft-tissue modelling for real-time MIS simulator can be found in [103] and [104]. In current research of tissue deformation for visuo-haptic simulation, commonly used frameworks are the Haptics3D (H3D) [60], the Simulation Open Framework Architecture (SOFA) [9], the Computer Haptics & Active Interfaces (CHAI3D) [58][71], the General Physical Simulation Interface (GiPSi) [105], and the ReachIn API.

The lumped-parameters model predicts the biomechanical response of the soft tissue by solving the partial differential equations via interpolation of the discrete nodes on the model. The distribution of the nodes insides the shape function forms a stiffness matrix that can be used to compute visual and haptic feedback during the interaction. Since the method does not incorporate all elements during the deformation estimation, the simulation speed is generally fast due to lower computational requirements as compared to mesh-based modeling solutions. Models derived from the mass-spring system modeling (MSM) method are commonly used to characterize and analyze the behavior of the tissue during interactions. The use of springs and dampers in Kelvin, Voigt, and Maxwell models, as well as extended viscoelastic models such as the Maxwell-Kelvin, Zener, and Wiechert models effectively emulate the viscoelasticity of soft tissue. Classic examples of the MSM applications can be found in the surgical training system with a deformable model for haptic and visual rendering [106]. Another example of lumped-parameters methods is the mass tensor method (MTM), where the model is formulated into a tetrahedron mesh with four displacement vectors of vertices assigned in each tetrahedron [107]. The parameters of the models are commonly identified by fitting the mathematical functions onto relaxation or creep profiles of the soft tissue and are then used to further investigate the response of the soft tissue model to desired input, such as frequency, and amplitude. These lumped models provide a fast prediction of the mechanical response of the tissue. However, they have limitations, i.e., they cannot accurately represent the dynamics and material properties of the tissue. Hence, models with higher fidelity are preferred for a more accurate and higher resolution visualization.

Two computational methods that allow for the incorporation of detailed anatomical features, and material models and properties are the finite element method (FEM) and the boundary element method (BEM). In the FEM, the entire domain is discretized with "finite elements (FE)". Each FE is defined by the location of its nodes and shape functions that estimate the variation of the field variable, e.g., displacement in tissue deformation, across the elements. The material model provides the link between stress and strain tensors. The elements are assembled to provide the equation of motion for the entire model. Solving these equations provides an estimation for the displacement field. The accuracy of the FE models of tissue deformation can be improved by using fine anatomical details of the tissues, which are usually obtained from medical imaging such as CT and MRI. FE models should also incorporate accurate material models and properties that can model the often nonlinear and rate-dependent responses of tissues. The FE modelling has been widely used in injury biomechanics to produce human body models for the prediction of injury under mechanical forces in, e.g., road traffic or sporting collisions. Two examples of detailed FE models of the whole human body are the THUMS [108] and GHBMC [109], which have been used for testing the safety of modern cars. Another example is the human brain models, which have shown that the location of maximal displacement predicted by the model correlated with the location of structural damage to the brain and even long-term effects [110]. Besides that, tissue deformation studies have also been performed using FEM to assess the behaviours and properties of the soft tissue during different displacement or interaction rates, and contact forces [111]. Such observations are very useful for medical procedures such as biopsy [112] and surgical planning [113]. The FE models of the human body and tissue can produce highly accurate predictions of tissue displacement and even tissue damage, but this comes with a high computational cost.

On the other hand, while the FE method discretises the entire domain, the BEM method discretises only the boundary, thus leading to fewer nodes and degrees of freedom. It allows sampling points within the domain for further interrogation. Although this approach may be faster for some applications, it can be computationally expensive if several field locations are interrogated. Several studies in surgery simulation have used BEM for predicting displacement in soft tissues, nose, and 3D facial models [114]. In contrast to FEM, implementing BEM for different problems is challenging, and as a result, there are only a few commercially available packages that have implemented BEM.

Studies that integrate both the lumped-parameters and the mesh-based models have the advantage of both fast computation and accurate predictions of nonlinear soft tissue responses. A classic example is the SOFA framework that can develop soft-tissue models in a modular way [115]. Multiple modeling methods are incorporated into the framework to compute real-time deformation effectively. Another combination example can be found in the investigation in [116] in which it obtained a 1D mathematical model by fitting the Zener model and Prony series to the relaxation curve of prostate tissue. The 1D model is used to study the transient and steady-state behavior of the tissue during instrument palpation to achieve the desired palpation force. The optimal model parameters obtained from the analysis can also be incorporated into FEM models [116].

2) Representation of Hand/Tools: Representation of hand/tools works based on the principle of increasing the awareness of hand movement with visual feedback correction [117]. Like a mouse cursor that can effectively inform our hand control precisely, showing the trainee the location of their hand on the patient can significantly improve their sense of presence in the virtual environment. This is particularly important in the virtual training setup, where the participant has restrictions on viewing their own hand. This is reflected in the visual environment design of many palpation training systems, such as [9]. In the case of MIS palpation, the representation of hand is normally replaced by the MIS tools [32].

3) Physiological Sounds: Physiological sound simulations are less investigated in the research of tissue examination simulators. Instead, some commercially available manikins included it as realistic features. The SimMan 3 G simulator presents Unilateral, Bilateral & lobar breath sounds, heart sounds at four anterior locations, and bowel sounds at four quadrants [8], see Fig. 2 a. However, they are currently only being simulated independently. The physiological sound simulation can be more informative if it is synchronized with other modalities such as haptic. For instance, the bone-cracking sounds in thoracic palpation can be correlated to the spine model during a virtual physical examination, and the breathing sound can be linked to chest movement lead by the tutor's verbal instruction during palpation.

B. Pain Expression for Closed-Loop Palpation

Pain evaluation during manual palpation is often used as feedback to assess a range of medical hypotheses for diagnosis. For instance, patients with existing conditions may experience discomfort or pain during abdominal palpation when the practitioner is assessing the tenderness. Such tenderness may be a sign of swollen tissue or inflammation; however, it may also be that the examining clinician is causing the patient discomfort in the absence of pathology. An effective interpretation of the patient's pain is critical as it also tells the examiner when to stop the palpation. The process of pain can ideally be separated into three phases.

In phase A, the patient's feelings will be triggered when the practitioner starts palpating on the patient. The feeling will then be encoded with a pain model, a representation of pain, with a particular format presented in Phase B. The practitioner will simultaneously decode and interpret the representation to form Phase C in interpreted pain. In the design of simulators, we are interested in phase B and its different formats. In general, there are two categories: realistic pain presentation that is portrayed by a human patient and augmented pain presentation that can only be introduced with artificial simulators. This is reflected in the diagram in Fig. 5

More specifically, pain expression methods in a realistic manner are facial expressions and verbal communication. Facial expression can be integrated into the training system by coupling the visual simulation to haptic simulation, while verbal communication is achieved via synchronized auditory simulation. By contrast, pain expression methods in the augmented information format can be much more diverse with the use of the robotic simulator and digital representation. Three major categories are introduced here with the help of auditory, visual, and haptic simulation, namely, numeric pain expression, vibrotactile feedback, and digital synthesized sound.

1) Facial Expression: Facial expressions enabled natural non-verbal communication between the practitioner and the patient. When correctly interpreted, facial expressions may convey additional information to the examiner, sometimes even more accurate than verbal response [118]. However, understanding the facial expressions of a patient is challenging for experienced practitioners, let alone medical students, due to significant variations of facial expressions in patients as a result of ethnicity, gender, and age. Several attempts of incorporating facial expressions in medical training simulators for different medical training processes such as dental training, pediatric training, emergency training have been reported [119]. These facial expression rendering systems proposed for medical training simulators are ranging from fully virtual to fully physical. However, attempts to develop facial expressions rendering as feedback for tissue examination training simulators are limited. [57] proposed a mixed reality human platform for breast cancer examinations. The left breast of the plastic manikin incorporates a soft phantom to simulate the breast skin, tissue, and underlying breast masses. The phantom also contained twelve pressure sensors to detect the user's touch. The virtual system was realized using a head-mounted display (HMD) and a wireless microphone. The facial expression of the mixed reality human showed discomfort during any touching of the breast, and pain when the user pressed in an area that was designated as painful during pilot experiments.

2) Verbal Communication: In general, vocal simulation is considered the primary channel to indicate pain as a complement to facial expression to evaluate tenderness in palpation [57]. However, it can be difficult to quantitatively present the pain level through verbal messages due to the variety in individual differences, culture, background, and language. However, it has unneglected advantages in providing a medical history or principal complaint in the form of debriefing. Previous research also shows integrating haptic feedback with verbal communication can significantly enhance the interpersonal communication skill of the practitioners [120]. In fact, the high bandwidth human-simulator communication enabled by verbal-haptic training can help the trainee exposure to a diversity of verbal responses in palpation in the proto-professional stage. This raises the potential to create a natural language data set in pain expression with associated diseased visual and haptic conditions. For instance, [57] reported the use of a keyword-based voice recognition approach in a breast palpation training system. The implementation allows the trainee to practice communication skills that facilitate the diagnosis based on a data set of 118 pairs of semantic questions and associated responses. This proto-professional experience can effectively increase the trainee's confidence level when they start to interact with real patients. In the process, the trainee can develop an expectation of the patient's response when they are palpating with certain strategies and asking certain questions.

3) Numeric Pain Expression: Numeric expression of the pain is not practical in clinical scenarios, but it can be very intuitive during the training process. It has been the most common approach in current sensor-embedded simulators to inform the trainee of their actions. [121] has demonstrated the use of numeric error bars to show real-time palpation pressure on four locations in a pelvic examination training system. In the Virginia Prostate Examination Simulator, four regions of finger pressures are also provided in real-time in the form of numeric error bars [62]. The embedded sensors and their associated measurements can be used to build a connection to the value of pain. However, none of those applications have yet built any theoretical model to present pain levels in clinical user studies.

The fundamental skill behind tissue examination is within the scope of sensor-motor coordination. Training with augmented numeric feedback before realistic scenarios and gradually removing the augmentation can be more effective and more precise than only training with realistic scenarios. However, there hasn't been any controlled comparison clinical study yet to evaluate medical palpation training performance with different pain representation modalities.

4) Vibrotactile Feedback: Vibrotactile feedback can be another way to represent the pain feedback to the examiners. Researchers have used it as a method to show object contact in training simulators since humans can detect and distinguish the high-frequency vibrations when object collision happens [122]. However, the implementation of vibration for pain expression is less explored in the field of simulator design. It is interesting as it can not only be used in the training phase but also has the potential to be carried in the real examination context as a wearable to translate assistive information for diagnosis.

5) Digital Synthesized Sound: Similarly, digital synthesized sound can be used as an alternative to numeric pain expression, considering that the visual sensation may be engaged with other clinical cues during the examination. It also has the potential to be implemented in wearables to facilitate the diagnosis.

C. Augmented Information for Assisted Learning

The most significant advantage of a R-SBE system is that additional augmented feedback that cannot be found in real scenarios can also be presented for effective training. A study of clinical breast examination based on augmented feedback proposed by [123] suggested that the non-natural tactile stimuli increase the training effectiveness in the sample of 48 medical students. The study provided two comparable scenarios: a natural scenario that simulates static breast lumps that mimic realistic physiological conditions and an augmented scenario that provides pulsating lumps via the oscillation. Even though such feedback is not realistic and can not be found in a real patient, training with such support increased the number of lumps detected, decreased the number of false positives, and improved the skill transfer [123]. Furthermore, simple information such as mistakes of the actions or contacts to the organs can also be informed to the trainee via augmented feedback. For instance, an ultrasound scanning training system adopted a Nintendo Wii Remote controller as the virtual probe that can vibrate when the operation is incorrect [124]. This type of augmented tactile information can also be transferred to the operator via wearables such as vibrotactile wristbands or wearable tactile devices [75].

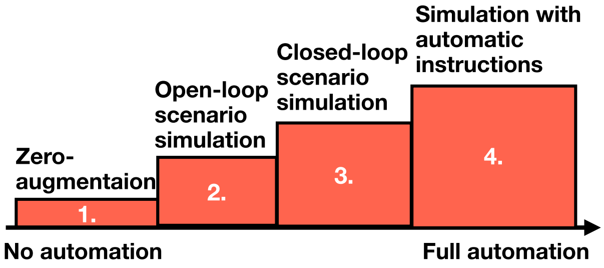

Fig. 6. Level of augmentation in robot-assisted palpation training.

The main idea is to merge the benefits of realistic feedback in palpation training with the augmented information offered by the artificial system to build a robotic patient that can reinforce the training process. Depending on the exact training context and the level of autonomy, augmented solutions can be formulated via instruction's voice, transparent organs, the pressure applied on individual tumors, articulated and instructed projection, vibrotactile feedback, and monitored palpation force and location.

The robotic simulator can provide simple open-loop augmented sensations at a low autonomy level, such as the pulsating lumps, which straightforward amplify the original feedback. Implementing human instruction and scoring based on diagnosis results would also be classified at the same level. At a higher autonomy level, the robotic simulator can form closed-loop feedback that provides augmented sensation based on the embedded sensor measurements of the actions. The training system should also be able to automatically evaluate the training performance after criteria designed by human experts. At the full autonomy level, the robotic system should real-time monitor the trainee's actions and simultaneously give instructions based on the data set. In this case, the simulator should generate its own criteria to compute specific training algorithms for each trainee. Fig. 6 shows a spectrum to explain the level of autonomy for augmented robotic-assisted training.

V. FUTURE DIRECTIONS

The study of the robotic palpation simulator starts around the mid-90 s, where researchers started to explore different methods to produce interactive haptic simulations. Using a haptic device to interact with simulated virtual patients on a computer screen is one of the most successful approaches. Such a method based on haptic devices has drawn many researchers' interest and quickly dominated the field until 2015. Part of the reason is because of the successful commercialization of haptic devices (such as the Phantom series manufactured by Sensable Technologies)

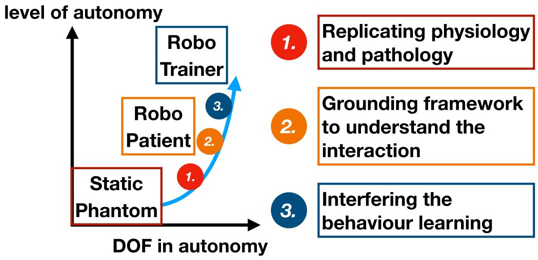

Fig. 7. The evolution of the medical simulators as it gradually move from a robot patient to a robot trainer.

and the fast development of open-resource computer models that can easily be implemented with the single interactive-point haptic input via a computer. The research in palpation training simulators has recently become diverse due to the advances in soft robotics, smart materials, control, and computational models. See Table II and Fig. 4.

In the first stage of designing the robot simulator, the aim is to mimic the human patient as similar as possible. However, it is neither effective nor possible to build a system that exactly represents/duplicates a human patient. The robotic system can go beyond just simulating human physiology and pathology. Indeed, it can simulate diverse and rare cases to provide more inclusive training schemes or show augmented artificial cues to further assist learning.

The next generation of training systems is facing the challenge of moving from a static phantom with zero autonomy of interaction towards a high autonomy level, similar to a human patient. With the increase of the level of autonomy in the simulator (based on multimodal sensors), the system has the potential to go beyond just a Robo-patient to a Robo-trainer (see Fig. 7). The evolution of such a transition arises based on the grounding problem [125], a framework to explain the complex tissue examination behavior. The robotic system can be an effective tool to help us investigate the entire interaction process initiated by the practitioners, such as the actions they took, the information they sense, and the reasons for their diagnosis. Thus, the Robo-patient simulator moves to the second stage, as a grounding framework is built to gain transparency of the interaction between the patient and the medical practitioner. Moreover, the tissue examination process can be formulated as a “frame-of-reference” problem or like Simon’s ant [126], where the complex interaction can come from simple yet effective strategies of the agent itself (in our case, the practitioner). As we distinguished the perspective of the observer and the agent itself, we can assume the little changes we introduced in the mechanism (a specific task induced by the robotic simulator) can cause significant changes in the agent behavior, where it builds on the system-environment interaction. At this point, we can push the training system to the third stage, where autonomous interfering from the robotic simulator leads to improved learning in the trainee. In other words, the system is no longer only a Robo-patient but also a Robo-trainer. It needs to be noted that the articulated interaction between the human user and the robotic system can never be fully anticipated in advance and not necessarily as well. Humans learn to keep an open architecture with loose and flexible boundaries when interacting with the environment, where physical and non-physical redundancies can be exploited to find the optimized adaptation. The interference provided by the robotic system can only be a small stimulus to lead but only assist learning. The aim is to optimize the trainee’s natural learning capability with a hint of “direction” computed by the Robo-trainer.

More specifically, we suggest following possible directions to be further studied by comparing the needs of the simulated palpation training system and the technology pushes.

A. Configurable Physical Interface

The development of a configurable physical interface aligns with the recent advances in smart materials, soft actuators, and sensors to create a more interactive physical training environment. This has been discussed in depth in Section. III-D. The basic principle of this trend is to 1) mimic human organs with computer-controlled actuators that can reassemble a variety of abnormal physiological conditions, 2) sense the palpation interaction (a consequence of the touch) with integrated sensors. Thus, the authors suggest two directions to develop training phantoms based on a configurable physical interface. First, researchers can explore tunable stiffness and configurable mechanisms in the field of soft robotics to create an entire soft-actuated phantom such as the 3D displays proposed by [127] and [84]. The second approach is to create a hybrid interface, where serial or parallel robots are introduced as the skeleton of the phantom to create large structural deformation while external layers of the configurable physical interface are used to simulate detailed physiological features.

B. Virtual Physical Modelling of Tissue and Finger Interaction to Support the Design of Physical Interface

In the physical surrogate model design, embedding soft sensors in the physical interface is an essential step to giving the phantom a degree of autonomy. The locations for the sensor placement significantly affect the sensor reading, and it depends on the tissue behavior during the palpation interaction. However, measuring and visualizing tissue behavior when in contact with external forces is often challenging on physical platforms. By contrast, high fidelity virtual physical modeling can simulate complex tissue interaction to reveal both changes in the tissue response and the fingers. It can allow us to make several iterations over design choices and identify the optimum locations for sensor placement to develop high fidelity and robust physical surrogate models. Visual feedback from within the tissue will also be useful to inform trainees on their perception and finger movements. The 3D model can be augmented with the physical platform integrated with tactile and force feedback, as demonstrated by [128] in rendering indentation forces onto the tissue for a more detailed visual cue to assist in this aspect.

C. Wearable for Augmented Sensory Cues

Currently, the area of introducing wearables in tissue examination training is less explored. However, the authors believe it has great potential in the next generation of medical training, where practitioners gradually learn to diagnose with assisted technologies. In this regard, the development of wearable for assisted manual examination covers two aspects: 1) it introduces a real-time reward mechanism via additional but intuitive feedback in the training phase to help the trainee to calibrate the tension in their arms and fingers; 2) it has the potential to be developed as a bed-side tool to facilitate diagnosis.

D. Multimodal Simulation With Both Physical Interface and the Virtual Augmentation

Another direction is to warp virtual visual feedback on the physical interface to create augmented reality training scenarios. This type of augmentation can further enhance the diversity of simulated physical conditions, particularly visual appearances such as facial expression, skin colors, or skin conditions. Furthermore, augmented feedback that can provide learning support can be projected on the physical system, for instance, transparent organs on the phantom to help the trainee understand which part of the organ they are examining. This is in alignment with Section. IV-C.

E. Smart Simulators to Support Palpation Behavior Study

Palpation is a technique that relies on the sensorimotor coordination of the practitioner to continuously explore new information about the physiological conditions while making decisions for diagnosis simultaneously. One solution to providing better training of palpation is to understand the science behind the technique better. The robotic approach can be promising for studying the behavior and strategies humans used in haptic exploration [129]. Considering the fact that it is both ethical and experimental difficult to study the practitioner's behavior when they are examining the real patient, it has great potential to further understand their behavior by asking the practitioner to palpate on a sensorized and condition-controlled phantom (a robotic patient) with sensing gloves to record the hand gesture and movement [130]. In such a process, the data collected through the robotic patient system can both provide a better training algorithm for the trainee and inform robotics on how to design a better artificial haptic diagnosis device.

F. Portable and Low-Cost Haptic Interface for Online Environment Virtual Training

Most of the current training methods are only suitable for laboratory environments due to the high manufacturing cost, large setup, control hardware, and high computational requirement of the computer. With the continuously increasing performance of personal computers and cloud-based computation, designing portable and low-cost haptic interfaces for medical training is another direction. The advantages are: 1) the trainee can have the device in their hand to practice at any time/location, thus, significantly increase the accessibility; 2) the device can be proposed to developing countries where there are limited medical training resources; 3) the interface can be distributed at both the trainer's side and the trainee's side to enable virtual training through the online environment, where it used to be difficult to convey knowledge on manual tissue examination techniques by videos or verbal instructions. This can be an alternative to the traditional theater-type training scenarios during global pandemics when the social distance is needed or when the living pattern starts moving to more virtual human-human interaction in the future.

G. Call for Future Research on Bench-Marking Methods for Training Effectiveness, Efficiency, and Accuracy

Among the 47 reported studies summarized in Table II, 23 publications involved human factor studies while 14 publications involved evaluation and validity with medical professionals. In the 14 studies that incorporate medical professionals, the average participant population is around 22 (with the lowest number of participants n=5 [80] and the highest number of participants n=64 [68]).

Most studies incorporate face validity with objective evaluation delivered by participants after practicing with the simulator. A common approach is by designing 4 to 7 point Likert-scale questionnaires to measure the feedback, such as the studies carried in [9], [65], [73], [75], [78], [80], [83], [87]. Example questions are *"How do you rate the haptic feeling of the finger in comparison to human soft tissue?"* [83]; *"How similar is the simulation output to the real one?"* [80]; *"The location of the arterial pulse in the real environment is correct and realistic"* [75]. Quantitative measurements to report the effectiveness and efficiency have been rarely adopted in the validation phase. The diagnose accuracy and time taken for the diagnosis for testing trials are reported in [16], [51], [54]. [62] reported the correct identification rate of the tumors for different simulators while [68] provided the construct validation process with a specific performance metric. Medical professionals' levels of experience are likely to be categorized between less than five years experience and more than five years experience for the human-factor study [9], [68]. However, there's no study that involves a detailed methodology that can be generalized to validate the effectiveness and efficiency of a physical examination simulator in R-SBE. There's a need for more future research on the bench-marking metric of face, construct, and predictive validity. In particular, methods to evaluate the long-term learning performance are needed from the field to provide strong evidence of the robustness and capability of R-SBE systems.

VI. CONCLUSION

This paper presents a thorough review of robotic simulators for medical tissue examination (palpation) training. We have analyzed the literature from a novel perspective to formulate the simulations with respect to multimodal sensory feedback. More specifically, the training scenarios rely on the replication of the multimodal haptic feedback rendering of the physiological conditions, but effective learning requires the collaboration of sensory modalities beyond just haptics. In this regard, we first categorized four major solutions in haptic rendering and discussed the technology implementation: 1) haptic devices for kinesthetic feedback, 2) tactile displays for cutaneous feedback, 3) haptic devices + tactile displays, and 4) configurable physical devices. See Table II and Fig. 4 for the detailed categorization based on 47 classic studies on palpation training simulators from 1992 to 2021. We also introduced a taxonomy based on two aspects, the objective of simulated features (from augmented feedback that is non-realistic to realistic feedback that simulates real patients) and the sensory feedback modalities, see Fig. 5. Critical objectives in palpation simulator design are discussed in this section as 1) enhancing realisticity with multimodal rendering with the advances in tissue deformation modeling, visual representation of hand/tools, and simulated physiological sounds, 2) pain expression for closed-loop palpation training achieved by facial expression, verbal communication, numeric pain expression, vibrotactile feedback, and digital synthesized sound, 3) augmented information for assisted learning.

We hope our survey and analysis can provide an overview of medical palpation training and how robotic simulators can benefit the learning process. Thus, increasing the visibility of this cross-disciplinary field with the medical practitioner, engineering researchers, and behavioral scientist and stimulating future research along the directions discussed above.

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