Haptic Feedback, Force Feedback, and Force-Sensing in Simulation Training for Laparoscopy: A Systematic Overview

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OBJECTIVES: To provide a systematic overview of the literature assessing the value of haptic and force feedback in current simulators teaching laparoscopic surgical skills.

DATA SOURCES: The databases of *Pubmed, Cochrane, Embase, Web of Science,* and *Google Scholar* were searched to retrieve relevant studies published until January 31st, 2017. The search included laparoscopic surgery, simulation, and haptic or force feedback and all relevant synonyms.

METHODS: Duplicates were removed, and titles and abstracts screened. The remaining articles were subsequently screened full text and included in this review if they followed the inclusion criteria. A total of 2 types of feedback have been analyzed and will be discussed separately: haptic- and force feedback.

RESULTS: A total of 4023 articles were found, of which 87 could be used in this review. A descriptive analysis of the data is provided. Results of the added value of haptic interface devices in virtual reality are variable. Haptic feedback is most important for more complex tasks. The interface devices do not require the highest level of fidelity. Haptic feedback leads to a shorter learning curve with a steadier upward trend. Concerning force feedback, force parameters are measured through force sensing systems in the instrument and/or the environment. These parameters, especially in combination with motion parameters, provide box trainers with an objective evaluation of laparoscopic skills. Feedback of force-use both real time and postpractice has been shown to improve training.

CONCLUSIONS: Haptic feedback is added to virtual reality simulators to increase the fidelity and thereby improve training effect. Variable results have been found from adding haptic feedback. It is most important for more complex tasks, but results in only minor improvements for novice surgeons. Force parameters and force feedback in box trainers have been shown to improve training results. (J Surg Ed 76:242−261. © 2018 Association of Program Directors in Surgery. Published by Elsevier Inc. All rights reserved.)

KEY WORDS: Haptic feedback, Force feedback, Force sensing, Laparoscopy, Simulation, Training

COMPETENCIES: Practice-Based Learning and Improvement, Medical Knowledge, Patient Care

INTRODUCTION

Acquiring surgical skills in a nonclinical setting through simulation includes fewer patient safety concerns and is less time consuming than traditional methods.[1-3] Moreover, simulation can be effectively used to train the more complex psychomotor skills necessary for minimal invasive surgery (MIS).[4] Simulation has therefore become an essential part of the training curriculum to prepare for minimal invasive procedures, such as laparoscopy.[5-7]

One of the main goals of simulation training is to create surgical realism at interactive rates.[8] This entails both a realistic environment as well as a realistic sense of touch, including haptic perception.[9] Haptic perception or feedback is a term used to describe the

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combination of tactile and kinesthetic perception.[10] Haptic perception and feedback are controversial subjects in laparoscopic training simulator design since haptic feedback is reduced and distorted during MIS because of the long instruments and friction inside the trocars. On the other hand, haptic cues are essential during surgery to control motor functions and render appropriate tissue handling skills.[11,12] Tissue handling should be gentle during surgery and require little force use, since it causes tissue reaction or even damage and consequently can result in intraoperative errors.[4,13] Better task performance is therefore associated with reduced force application.[14-16] Training should focus on improving tissue-handling skills by proper use of force.[14]

Currently available simulating methods can be subdivided into box-training, virtual reality (VR) and augmented reality (AR) training. A box trainer (BT) provides real haptic feedback but lacks a realistic environment and objective results. VR on the other hand lacks haptic feedback but provides objective results. AR provides both haptic feedback during training and objective results.[2]

Haptic feedback has been suggested to improve simulation training. In VR-trainers, haptic interface devices have been developed to create artificial haptic feedback, while BTs, which already provide natural haptic feedback, are supplied with force sensing and force feedback mechanisms to improve training results.[10,16-28] Although haptic and force feedback have been widely recognized as important concepts within laparoscopic simulation training, several issues have remained unresolved. These issues surround the characteristics that will result in optimal skill acquisition, such as fidelity of a simulator and the composition of the optimal training curriculum.

With this literature overview, we aim to assess the benefits of force and haptic feedback in laparoscopic simulation. Should force and haptic feedback be used in laparoscopic simulation and more specifically when training skill acquisition and tissue manipulation? The available literature on haptic feedback, force feedback, and force sensing in simulation training used for laparoscopic surgery will be researched.

METHODS

A systematic search was conducted in *Pubmed*, *Embase*, *Cochrane*, *Google Scholar,* and *Web of Science* to retrieve relevant studies published until January 31st, 2017. The search method developed for each database comprised of relevant synonyms of haptic and force feedback and force sensing, simulation, and laparoscopy (Table 1).

One assessor (EO) removed duplicates and subsequently screened the titles and abstracts of all remaining articles for inclusion. Articles were included if they focused on either haptic or force feedback or force sensing in simulation training for laparoscopy. Articles included in this systematic literature review include experimental studies as well as patent applications, opinionated papers, and editorials about both haptic and force feedback. Review articles were excluded since they do not present original data. They were, however, assessed for relevant references. Since haptic rendering is a process independent of the haptic interface devices, articles solely describing the development of algorithms enabling force feedback or calculating deformation were excluded. The in- and exclusion criteria are summarized in Table 2. The remaining articles were screened full text by 2 assessors (EO and TH). Any disagreements regarding selection and inclusion of articles were resolved through consensus. Each selected article was hand searched for relevant cross-references as were any reviews on the subject.

Haptic, force, and tactile feedback are terms that are often used disorderly. In this article, haptic feedback is used to describe the combination of kinesthetic and tactile feedback, whereas tactile feedback is used to describe the perception of pressure, vibration, and texture. Force feedback on the other hand is used to describe the actual feedback provided by a device concerning the use of forces and torques.

Since this review involves haptic feedback as well as force feedback and force sensing, the articles identified cover a wide range of different subjects. Haptic feedback in VR simulation and force feedback in box training will be separately discussed. We will first discuss VR trainers. The types of haptic interface devices that have been designed to create artificial haptic feedback, the necessary fidelity level and articles discussing the effect of haptic feedback in VR trainers on training results will be covered. Subsequently, we will elaborate on force sensing and force feedback in BTs by discussing force measurement systems, force parameters, and the effect of force feedback. Finally, different types of simulating trainers will be compared to one another.

RESULTS

Search Strategy and Study Selection

A total of 4023 potentially relevant articles were retrieved through the search, of which 87 original articles could be used in this review. The articles were not individually appraised since many of studies included are descriptive and were ineligible for such appraisal. Figure 1 displays a flow chart of the study selection process.

TABLE 1. Search Methods

Database	Search	Syntax	Results
PubMed	#1	(((haptic [tiab] OR tactile [tiab] OR tactual [tiab]) OR (force* [tiab] OR power* [tiab] OR strength* [tiab] OR tensile [tiab] OR intrinsic [tiab] OR pressure [tiab] OR (mechanical [tiab] AND process* [tiab]) OR "Mechanical Processes"[Mesh]) AND (feedback [tiab] OR assessment [tiab] OR evaluation [tiab] OR reaction [tiab] OR repl* [tiab] OR response* [tiab]) OR "Feedback"[Mesh])) OR (((force* [tiab] OR power* [tiab] OR strength* [tiab] OR tensile [tiab] OR intrinsic [tiab] OR pressure [tiab] OR (mechanical [tiab] AND process* [tiab]) OR "Mechanical Processes"[-Mesh]) AND (sense [tiab] OR sensing [tiab] OR measure [tiab] OR measurement [tiab] OR analysis [tiab] OR amount [tiab] OR appraisal [tiab] OR assessment [tiab] OR evaluation [tiab] OR "Weights and Measures"[Mesh])))	593
	#2	((simulation* [tiab] OR imitation* [tiab] OR reproduction* [tiab] OR "simulation model" [tiab] OR (physical [tiab] AND model* [tiab]) OR "virtual reality" [tiab] OR "augmented reality" [tiab] OR "box trainer"[tiab]OR "box training"[tiab] OR (box [tiab] AND train* [tiab]) OR ((surgical[tiab] OR skill*[tiab]) AND training[tiab]) OR "Computer Simulation"[Mesh]))	
	#3	((laparoscop* [tiab] OR peritoneoscop* [tiab] OR celioscop* [tiab] OR endoscop* [tiab]) OR (((laparoscopic [tiab] OR endoscopic [tiab]) OR (minimal [tiab] AND invasive [tiab])) AND ((surgical [tiab] AND procedure* [tiab]) OR surgery [tiab] OR surgeries [tiab])) OR "Laparoscopy"[Mesh] NOT (flexible [tiab] AND endoscopy [tiab]))	
	#4	#1 AND #2 AND #3	
Embase	#1	"tactile feedback"/exp OR 'tactile feedback':ab,ti OR "haptic feedback":ab,it OR "tactual feedback":ab,ti	994
	#2	haptic:ab,it OR tactile:ab,ti OR tactual:ab,ti	
	#3	force:ab,ti OR power:ab,ti OR strength:ab,ti OR tensile:ab,ti OR intrinsic:ab,ti OR pressure:ab,ti OR "mechanical process":it,ab OR forces:ab,ti OR powers:ab,ti OR strengths:it,ab OR "mechanical processes":ab,ti	
	#4	"feedback system"/exp OR feedback:ab,ti OR assessment:ab,ti OR evaluation:ab,ti OR reaction:ab,ti OR reply:ab,ti OR response:ab,ti OR assessments:ab,ti OR evaluations:ab,ti OR reactions:ab,ti OR replies:ab,ti OR responses:ab,ti	
	#5	"measurements"/exp OR measurement:ab,ti OR sense:ab,ti OR sensing:ab,ti OR measure:ab,ti OR measurementab,ti OR analysis:ab,ti OR amount:ab,ti OR appraisal:ab,ti OR assessment:ab,ti OR evaluation:ab,ti	
	#6	#1 OR ((#2 OR #3) AND #4) OR ((#2 OR#3 AND #5)	
	#7	"simulation"/exp OR simulation:ab,ti OR imitation:ab,ti OR reproduction:ab,ti OR model:ab,ti OR models:ab,ti OR "simulation model":ab,ti OR "virtual reality":ab,ti OR "augmented reality":ab,ti OR "box training":ab,ti OR "box trainer":ab,ti OR ((surgical:ab,ti OR skills:ab,ti) AND training)	
	#8	"laparoscopy"/exp OR laparoscopy:ab,ti OR peritoneoscopy:ab,ti OR celioscopy:ab,ti OR "endoscopy":ab,ti OR videolaparoscopy:ab,ti	
	#9	#6 AND #7 AND #8	
Cochrane	#1	tactile:ti,ab or haptic:ti,ab or tactual:ti,ab	67
	#2	force:ti,ab or power:ti,ab or strength:ti,ab or tensile:ti,ab or intrinsic:ti,ab or pressure:ti,ab "mechanical process":ti,ab	
	#3	"feedback system":ti,ab or feedback:ti,ab or assessment:ti,ab or evaluation:ti,ab or reaction:ti,ab or reply:ti,ab or response:ti,ab or assessments:ti,ab or evaluations:ti,ab or reactions:ti,ab or replies:ti,ab or responses:ti,ab	
	#4	MeSH descriptor: [Mechanical Processes] explode all trees	
	#5	MeSH descriptor: [Feedback] explode all trees	
	#6	(#1 or #2 or #4) and (#3 or #5)	
	#7	measurement:ti,ab or sense:ti,ab or sensing:ti,ab or measure:ti,ab or measurement:ti,ab or analysis:ti,ab or amount:ti,ab or appraisal:ti,ab or assessment:ti,ab or evaluation:ti,ab	
	#8	MeSH descriptor: [Weights and Measures] explode all trees	
	#9	(#2 or #4) and (#7 or #8)	
	#10	simulation:ti,ab or imitation:ti,ab or reproduction:ti,ab or model:ti,ab or models:ti,ab or "simulation model*":ti,ab or "virtual reality":ti,ab or "augmented reality":ti,	

(continued)

TABLE 1 (*CONTINUED*)

Database	Search	Syntax	Results
		ab or "box training":ti,ab or "box trainer":ti,ab or "surgical training":ti,ab or "skills training":ti,ab	
	#11	MeSH descriptor: [Computer Simulation] explode all trees	
	#12	laparoscopy:ti,ab OR laparoscop*:ti,ab or peritoneoscop*:ti,ab or celioscop*:ti, ab or "endoscopy":ti,ab or videolaparoscop*:ti,ab or ((surgical:ti,ab and procedure:ti,ab) or surger*:ti,ab and laparoscop*:ti,ab)	
	#13	MeSH descriptor: [Laparoscopy] explode all trees	
	#14	(#6 or #9) and (#10 or #11) and (#12 or #13)	
Google Scholar	#1	((~haptic OR ~force) AND ~feedback) OR ((~force AND ~sensing))	1.430
	#2	~simulation OR ((~skills OR ~surgical) AND ~training)	
	#3	(~laparoscopy OR ~endoscopy) NOT ~flexible	
	#4	((journal AND paper) OR 'journal paper')	
	#5	#1 AND #2 AND #3 AND #4 + last 5 years (2011)	
Web of Science	#1	(TS = haptic OR TS = tactile OR TS = tactual) AND (TS = feedback OR TS = assessment OR TS = evaluation OR TS = reaction OR TS = repl* OR TS = response*) OR (TS = force* OR TS = power* OR TS = strength* OR TS = tensile OR TS = intrinsic OR TS = pressure OR (TS = mechanical AND TS = process*)) AND ((TS = sense OR TS = sensing OR TS = measure OR TS = measurement OR TS = analysis OR TS = amount OR TS = appraisal OR TS = assessment OR TS = evaluation) OR (TS = feedback OR TS = assessment OR TS = evaluation OR TS = reaction OR TS = repl* OR TS=response*))	939
	#2	(TS = simulation* OR TS = imitation* OR TS = reproduction*) OR TS = "simulation model" OR TS = "physical model" OR TS = "virtual reality" OR TS = "augmented reality" OR ((TS = box AND TS = train*) OR (TS = surgical OR TS = skill*)) AND (TS = train*)	
	#3	(TS = laparoscop* OR TS = peritoneoscop* OR TS = celioscop* OR TS = endoscop* NOT TS = "flexible endoscopy") OR ((TS = laparoscopic OR TS = endoscopic) OR (TS = minimal AND TS = invasive)) AND ((TS = surgical AND TS = procedure*) OR TS = surger*)	
	#4	#1 AND #2 AND #3	

Date of search: 31-01-2017

TABLE 2. In—and Exclusion Criteria

Inclusion criteria
- Corresponding domain and determinants
- Haptic or force feedback; force sensing
- Simulation trainers
- Laparoscopy
- Original data
Exclusion criteria:
- Systematic reviews
- Flexible endoscopy
- Colonoscopy
- Endoscopic surgery simulator
- Neurosurgery
- Robotic surgery
- Vascular surgery
- Natural orifice transluminal endoscopic surgery (NOTES)
- Trocar/Needle insertion training system
- Algorithm
- Haptic rendering

VR Simulation

Haptic Interface Devices in VR Training

The majority of the studies identified covered the design of a haptic interface device build for VR trainers or described the use of these devices. A total of 39 articles elaborated on this subject.

Several articles describe the development of a simulator with haptic feedback. By far the most often described device is the PHANToM, an invention of Thomas Massie at MIT and issued by SensAble technologies.[26-33] Instead of using the PHANToM device, some researchers have themselves developed a device or a complete simulator with haptic feedback incorporated.[10,27,34-50] The developed simulators cover different laparoscopic procedures such as cholecystectomy,[26] herniorhaphy[40] and laparoscopic adjustable gastric band surgery[33] or basic laparoscopic tasks such as the tasks used in the fundamentals of laparoscopic surgery program,[31] palpation techniques[42] and cutting tasks.[50]

Fidelity of the VR simulator. Fidelity describes the resemblance of a simulator to the actual surgical procedure in the operating room.[51] The combination of mechanical actuators and the software system defines the fidelity of a haptic interface device. Fidelity of a simulator device is thought to affect training results.[30,35-38,48,51,52,54,55] Haptic devices are thought to be most realistic when they

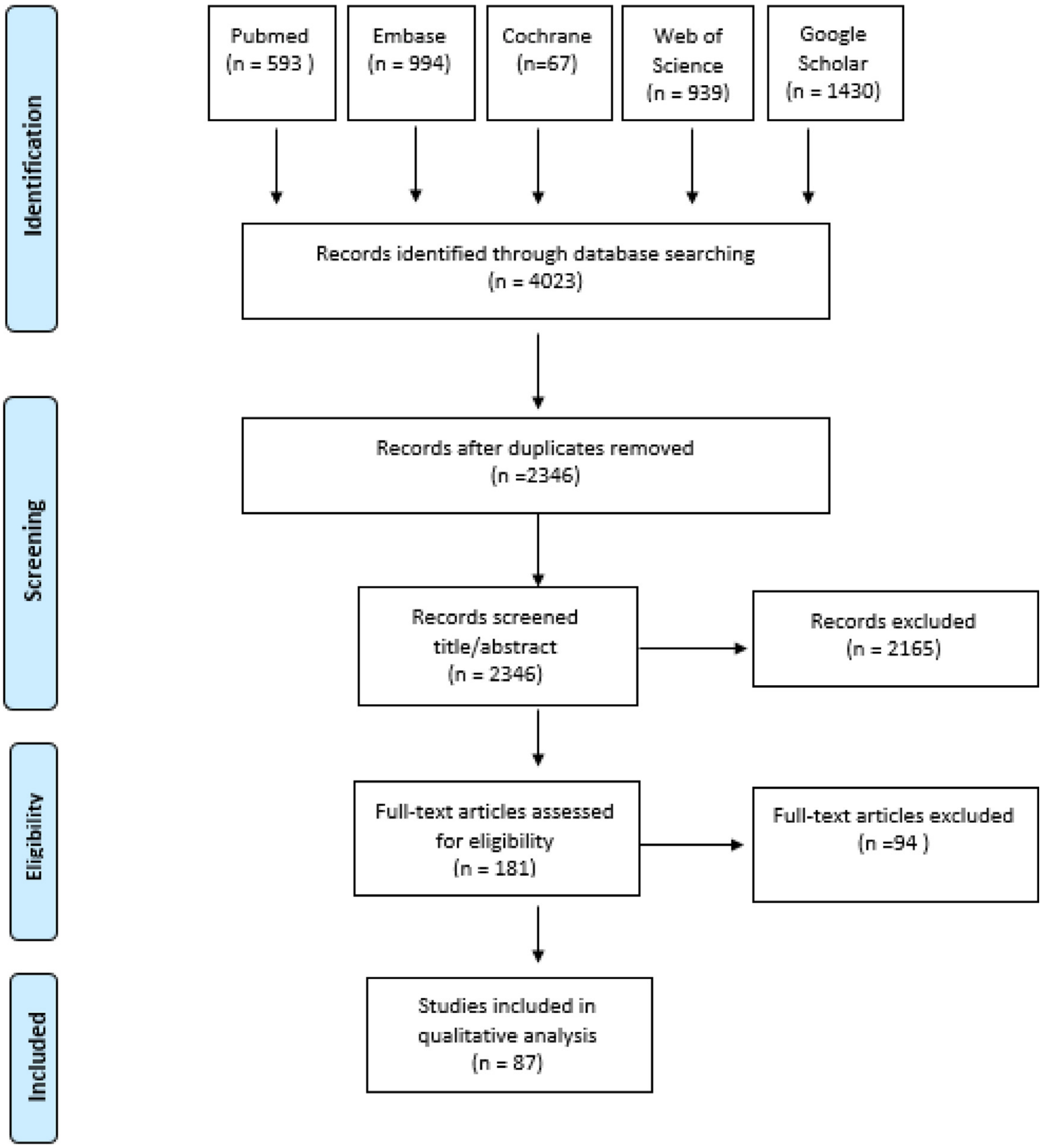

FIGURE 1. Study selection process.

feature compactness, high sustained output force capability, low inertia, low friction, high structural stiffness, 0 backlash, an absence of mechanical singularities, good responsiveness, and narrow-ranged bandwidth.[35-38,46] The degrees of freedom (DOF) of the different haptic interface devices described in the literature range from 2 to 6. Devices with 2 DOFs are solely capable of simulating a movement such as poking or swinging in a single plane, while a device with 6 DOFs facilitates more complicated movements and actions in multiple directions. A human body allows for a total of 6 DOF: forward/backward, up/down, left/right, pitch, yaw, and roll.[55] Due to limitations of a surgeon's workspace, this number is decreased to 4 DOFs during laparoscopic surgery.[37] The highest fidelity is reached when the haptic interface device possesses the amount of DOFs similar to those available during laparoscopy.[51] A higher number of DOFs on the other hand can negatively affect other mechanical properties such as inertia. Some studies therefore encourage using fewer DOFs.[26,35,53,54] The software system of the device can further employ different methods to imitate tissue properties, which can be divided into linear and nonlinear methods. Force-displacement of real human tissue is nonlinear. Linear methods, however, are easier to achieve. Although fidelity is higher with a nonlinear mechanism, Kim et al. found practically identical training effectiveness for both methods.[51] Since haptic feedback devices are complicated to build and entail additional costs, Hiemstra et al. have proposed an alternative method to raise fidelity. They propose to adjust the kinematic behavior of objects in a VR environment by adding the instrument velocity and physical properties of the objects. A software program was used that was able to add kinematic interactions to the objects in the VR trainer that were based on velocity of laparoscopic instruments and on the physical properties of the concerning objects. This has been found to improve learning curves compared with VR trainers without kinematic interaction.[52]

Haptic Feedback in VR Training

Surgeons have indicated during a preliminary analysis that they consider lack of tactile feedback the most important weakness of VR trainers and that haptic feedback is sometimes even more important than visual feedback.[55,56] At the same time, they are critical about the currently available systems and prefer the natural haptic feedback such as available in fresh frozen cadavers to the simulated haptic feedback in VR trainers.[57] Additional friction caused by haptic feedback for instance, is thought to interfere with the haptic sensation, counterbalancing the added realism, and confusing an inexperienced operator.[58-60] Additionally, haptic feedback is sometimes considered an unnecessary stimulus for novice surgeons during training. Presumably, while acquiring a surgical skill, novice surgeons have less spare attentional resources to attend to these haptic cues.[11] The benefits of adding haptic feedback to simulators aimed at inexperienced surgeons is therefore questionable. The following section describes the research executed to investigate the effect of haptic feedback in VR simulators on training results and learning or performance curves.

Training results and haptic feedback. A total of 8 studies compared the training results of VR trainers with haptic feedback devices to those without.[7,11,53,61-64] Table 3 provides an overview of these studies. A significant difference between devices with and without haptic feedback is found in 6 studies,[11,30,53,61,62,64] while 2 studies do not present a significant difference.[7,63] Several important differences can be identified between these studies that might explain the contradicting results. First, different types of tasks have been performed ranging in difficulty. Second, studies use several different outcome measures to assess task performance. Third, the test protocols used, vary between studies. For example, Panait et al. let participants perform tasks in both the nonhaptic and haptic setting,[62] while participants are split into 2 groups that are trained in either a haptic or nonhaptic setting in other studies.[62] Finally, studies use different types of simulators and haptic interface devices with varying levels of fidelity. The difference in performance between the simulators used could have resulted in contradictory result. Comparing simulation trainers with different levels of fidelity, Khan et al. report that if haptic feedback is added to a device, skills improve significantly more.[30] Therefore, the differences in fidelity levels between studies alone cannot be satisfactorily used to clarify contradicting results between studies.

One study on the effect of haptic feedback is not included in Table 3. This study concludes that time to complete a task is significantly lower when haptic feedback is provided. However, the setting without haptic feedback also lacks visual feedback. Therefore, it is impossible to distinguish the effect of haptic feedback from the effect of visual feedback.[32]

Overall, it seems that advanced tasks requiring superior precision, benefitted more from haptic feedback than basic tasks,[62] specifically once more accuracy and delicate tool control are required.[53] Needle driving tasks also benefit more from haptic feedback during training than knot-tying tasks.[64] The effect of haptic feedback on training results is most significant at the beginning of training.[64] Concerning outcome measures, 5 studies demonstrate that the time to complete a task is shorter as a result of haptic feedback.[11,53,62,64,65] On the other hand, instrument movement is slower[7] and tracking time similar for VR trainers with and without haptic feedback.[63]

The usefulness of haptic feedback for novice surgeons in the skill-acquisition phase was investigated by Cao et al.[11] They apply a method called cognitive loading. This method reduces the available attentional resources by asking participants to solve mental arithmetic problems while executing a task on the VR trainer. Haptic feedback was found to counteract cognitive loading. The beneficial effect of haptic feedback increased when participants were more experienced with laparoscopic surgery.[11]

Learning or performance curve and haptic feedback. Since it is not possible to measure learning directly, performance scores, which combine different outcome measures, are often used. A performance or learning curve is then created from the scores acquired when a task is completed multiple times.[2] The learning curve associated with laparoscopy is known to be very gradual. At least 100 practice cases are recommended for more complex procedures.[16] VR trainers accelerate this process in novices and experts.[66,67] The effect of VR trainers is most significant during the early part training.[67] A total of 4

TABLE 3. Effect of Haptic or Force Feedback on Performance Scores on VR Trainers

Article	Participants		Type of simulator	Task	Independent Measure	Dependent Measure	Conclusion
	N	Type					
Cao et al.[11]	30	No, I, E	MIST-VR ProMIS	Transfer-place task	- Cognitive loading - Haptic feedback Experience	- Time to task completion - Errors - Number of math problems solved	Haptic feedback enhances performance and counterbalances cognitive load.
Kim et al.[53]	24	No	Self-developed with Phantom	Pulling and cutting	Haptic feedback: linear, nonlinear, no feedback	- Total Performance Score - Time - Cut Accuracy - Push Accuracy - Obstacle Avoidance	Skill transfer improves with haptic feedback. No difference between linear and nonlinear model.
Khan et al.[30]	25	No, E	Mouse Joystick with/without haptic feedback Phatnom Omni Hand Manipulator	Poking and precision Peg transfer	Fidelity of simulator	- Economy of movement - Speed - Precision	Haptic feedback improved result even on simulators with a lower fidelity such as a joystick.
Lamata et al.[79]	32	No, I, E	Self-developed with Phantom	Pulling and pushing	- Experience - Visual feedback Haptic feedback	- Tissue consistency - Confidence - Tissue identification	If tissue consistency information is to be delivered, haptic feedback is necessary.
Panait et al.[62]	10	No	Self-developed with Phantom	Peg transfer Pattern cutting	- Haptic feedback	- Time to complete task - Grasping tension - Instrument path length - Dexterity - Missed objects - Tissue damage	Haptic feedback improves performance measures and reduces errors especially for advanced tasks.
Salkini et al.[7]	20	No	Simbionix LapMentor II	Grasp, Pul and Cut	- Haptic feedback - Videogame playing	- Accuracy - Economy of movement - Average speed	Less effect of haptic feedback on performance than hypothesized.
Thompson et al.[63]	33	No	Simbionix LapMentor II	Cholecystectomy; Basic tasks	- Haptic feedback	- Time - Efficiency - No of movements - Path length Speed	No significant effect of haptic feedback.
Zhou et al.[64]	20	No	MIST-VR ProMIS	Knot tying	- Haptic feedback	- Time to complete	Significant difference especially in first 5 hours.

TABLE 4. Effect of Haptic Feedback on Learning Curves in VR Trainers

Article	Participants		Research method	Groups			Outcome Measure
	N	Type					
Kim et al.[53]	24	No	Training results pre and post test	VR with linear haptic feedback	VR with nonlinear haptic feedback	Control	- Total Performance Score - Time - Cut Accuracy - Push Accuracy - Obstacle Avoidance
Ström et al.[9]	38	I	Post test	VR with early haptic feedback	VR with late haptic feedback	-	- Total Performance Score
Thompson et al.[63]	33	No	Post-test training	Haptics	No haptics	Control	- Time - Efficiency - No of movements - Path length - Speed
Zhou et al.[64]	20	No	Post test	Haptics	No haptics	-	- Time to complete successful knot - Instrument path* - Instrument smoothness* - Error* - Overall score*

AR = Augmented reality; Box = boxtrainer; VR = virtual reality.
E = expert; I = intermediate; No = novice.
SP = single port; TP = 2 port.
*Outcome measures restricted to either the haptics or the no haptics simulator.

studies have evaluated the learning curves of VR simulators with and without haptic feedback.[9,53,63,64] An overview of these articles is presented in Table 4.

The effect of haptic feedback on the learning curve seems to depend on the task performed. The learning curve of participants training with haptic feedback performing basic tasks started at a much higher level, was more regular, showed a more steadily upward trend, and showed less variability between the participants when compared to learning curves obtained in a setting without haptic feedback.[53] The effect of haptic feedback on learning curves is most significant in the early training phase.[9] When performing more complicated tasks, the difference between learning in a haptic and nonhaptic setting were not found to be significant.[63] Knot-tying tasks in a VR simulator with haptic feedback resulted in steeper learning curves and less variance between subjects compared to a simulator without haptic.[64]

Force Feedback and VR

The use of force feedback to improve skill acquirement is most often attributed to BTs. A total of 4 studies have discussed force feedback in a VR setting.[10,24,68,69] Novices were found to apply significantly higher amounts of force for both basic and more complex probing and grasping tasks and basic sweeping tasks than experts in a VR setting and to use more abrupt tool movements.[24,68,69] Visual force feedback improved force and motion parameters of residents on both basic and more complex tasks in a VR trainer.[68] Force feedback has also been effectively used during VR training, to teach novices how far to insert laparoscopic tools.[10]

BTs

Force Measurement Systems

The ability of measuring forces is separately added to BTs. These force measurement sensors can be divided into 2 different categories; force sensors in the instrument, and force sensors in the environment of the instrument. Force sensors in the instruments measure a representative of the force exerted with the instrument tip on the surroundings. Force sensors in the environment measure a representative of the reaction force and can be located in and under the training task or at the instrument incision site.

Sensors in the instruments should not restrict or influence the instrument movements during training. When the sensor is placed in the instrument shaft, it is preferably small and often built out of layers of piezoelectric, resistive, optical, or capacitive materials.[70-73] This approach requires significant modification of the instrument but can provide a relatively good output in terms of sensitivity, accuracy, and force direction as all the forces are transmitted through the sensor. If instrument modification is not allowed, strain gauges glued on, or placed around, the shaft can be used to measure the strain in the metal shaft due to bending of the instrument.[74] Strain gauges, however, are influenced by temperature changes and the glue is not resistant to chemicals and autoclave sterilization. As the force is not transmitted through the gauges directly the output/stress relation needs to be determined through calibration. Independent of the location of the sensors on the instrument, there is always a connection between sensor and controller that potentially influences the user.

There are 3 important advantages of forces measurement in the direct environment of the instrument over integration of a force sensor in the instrument. First, standard instruments can be used and changed during the training based on the user's preference. Second, there is no critical size requirement for the sensor as it is often located under or in the training task.[17,18] Third, deformation of force sensors integrated in or under a training task is allowed to some degree as the tissues that are manipulated are also highly deformable. A force sensor integrated in the instrument should not influence the instrument stiffness of the instrument. It is therefore much more expensive to build. A disadvantage of a signed force sensor under the task is the measurement of reaction forces only. It can therefore be impossible to determine which of the 2 instruments exerts force on the task. By placing 2 sensors between the 2 instrument shafts and top plate at each of the incision sites, the contact force for each instrument can be used as an additional source of information for bimanual skills assessment.[75]

Force-Sensing for Assessment of Surgical Skills

Force can be used as a parameter in the training of laparoscopic skills such as grasping[16] and palpation[25] or as a measure of tissue manipulation in general.[76] It can also be used in trainers to provide feedback to the users. Grasping tissue results in a combination of different forces exerted on the tissue, including pinch forces to grab the piece of tissue and pull forces moving the tissue elsewhere. The combination of these forces influences whether tissue will slip, be damaged or is grasped successfully. Using a force-sensing grasper during laparoscopic surgery, Susmitha et al. have found that more surgical experience leads to a reduced use of pinching force, as do tissue type and visual feedback.[16] It was further found that novices applied significantly higher amounts of force for probing, sweeping, and grasping tasks than experts in VR simulators.[24]

An assortment of possible force parameters is mentioned in the literature. The most often used parameters are maximum absolute force and mean absolute nonzero force, which is the force averaged across all samples during the time that the force exerted was above 0. Some parameters are not directly measured, but can be calculated such as the rate of change (derivative of used force) and total force use over time (integral of used force).[77] Table 5 provides an overview of the different force parameters.[15,17,18,75-81] Force use is thought to be a direct measure of tissue handling skill. This is a measure of how roughly the tissue is treated and if tissue damage has occurred. Damage to tissue occurs when more than 1.5 N of tractive force is used during suturing.[4]

The use of force-based metrics is a better indication of performance than metrics of time or position information alone.[77] It is recommended to use a combination of different parameters to assess tissue handling skills. Assessment of the training of novice and intermediate surgeons especially should include force parameters as well as motion parameters such as pathway and position information.[75] Both expert and novice surgeons have been found to misinterpret use of force, which results in excessive use of force by both groups. Training with force feedback and force parameters is therefore hypothesized to be beneficial for both novices and experts.[14]

Differentiating Power

Discrimination between different levels of experience is thought to be a good measure of the training ability of a simulator. Table 6 displays results of the different studies on this subject. Level of experience is dependent upon the amount of accomplished laparoscopic procedures or the postgraduate year.

Table 6 demonstrates that the differentiating power of force parameters varies for different task sets. Force parameters on a cutting task are not able to discriminate between novices and experts,[77] while the result of force use during peg transfer and needle driving does differ significantly between novices and experts[18,19] and between novices, intermediates and experts.[17] Results of more difficult tasks such as tissue handling, suturing and knot tying are more ambiguous. Trejos et al. have found the strongest correlations between experience and force-based metrics during suturing and knot-tying tasks.[77] Cundy et al. also report significant differences in mean force application during a task involving suturing and intracorporeal knot tying.[22] Horeman et al. describe that despite the high discriminating power of the parameters that represent the maximal force value measured, the mean force value and force variability are not strongly correlated to surgical experience during knot tying due to minimal contact between tissue and instrument tips.[20] Concerning tissue handling, Horeman et al. found that discrimination was best measurable by combining motion and force parameters in more dynamic tasks.[75] Correlations during a tissue handling task in the

TABLE 5. Overview Different Force Parameters

Force Parameter	Definition	In	Used in
Maximum absolute force	Maximum value in the absolute force vector	Newton	Cundy et al.[17] Hanna et al.[15] Horeman et al.[18,75,76] Rodrigues et al.[12,80]
Mean absolute nonzero force	Averaged mean absolute force of periods during training in which the force was not 0	Newton	Cundy et al.[17] Horeman et al.[18,20,75] Rodrigues et al.[12,80] Wottawa et al.[81]
Mean absolute force	The total mean absolute force during measurement	Newton	Horeman et al.[78] Rodrigues et al.[12]
Force volume	Volume spanned around the 3 largest standard deviations of the force in an ellipsoid	Newton/second	Cundy et al.[17] Horeman et al.[75,78] Rodrigues et al.[12,80]
Maximum force area/peak force	The maximum force area indicates the largest force area. This is created between the moment in time when the absolute force becomes higher than 0 until the moment it becomes 0 again.	Newton-seconds	Horeman et al.[78] Wottawa et al.[81]
Peak to peak value	Sum of the tissue reaction force and 2 times the trocar friction. A complete cycle of pulling tissue.	Newton	Lamata et al.[79]
Maximum temporal slope	The maximal increase rate of the amount of force used.	Newton/second	Lamata et al.[79]
Force range	The differences between the minimum and maximum force applied during a task	Newton	Trejos et al.[77]
Interquartile range	This only takes into account the 50% of the data closest to the median	Newton	Trejos et al.[77]
Force area/integral of the force	A measure combining the total force used over a certain time.	Newton/second	Trejos et al.[77]
Force derivatives	The derivatives of force can indicate the consistency and rate of change of the applied force.	Newton/second	Trejos et al.[77]
Smoothness of the applied force	Measured as the third derivative of force, it calculates the regularity and uniformity of the contact force.	Newton/second	Trejos et al.[77]
Left and right maximum abdominal force	This represents the absolute abdominal force in the left and the right trocar	Newton	Horeman et al.[76]
SP maximum abdominal force	The absolute abdominal force in the single-port trocar	Newton	Horeman et al.[76]

study by Trejos et al. were significant for many force parameters, but not as strong as those during suturing and knot-tying tasks.[77] An important difference between these studies is that Trejos et al. use sensitized laparoscopic instruments to measure tool-tissue interaction forces at the tip of the instrument,[77] while the other studies measure the forces exerted on the tissue.[17,20,75] One study is not included in Table 6 since it is not reported whether or not differences are significant.[25] It reports that mean force use of novices and experts showed very different patterns. While experts tended to use overall low forces with a characteristic peak at the end of the task as they tighten the knot, novices used much higher forces throughout the entire task.[25]

Although the exact parameters used as performance metrics for different tasks are variable, several differences between novices and experts have been clarified. Novices tend to use higher mean forces than experts.[17,18,20,22,77] The used forces are higher in the course of the complete task with higher peak forces and bigger force volumes for most complex tasks. While tying a knot, novices tend to exert higher maximum forces for longer periods of time and the regularity and smoothness of the applied forces are significantly better for experts.[20,25,77]

Force Feedback

A total of 9 studies have concentrated on using force feedback in BTs. Feedback can be provided in 3 different ways: auditory, visual, and haptic feedback. Since auditory feedback is unpractical in an operation room (OR)-setting, only visual and tactile feedbacks have been investigated.[82] Minimizing the time delay between the movement and feedback is essential to create realistic instrument movement.[19]

TABLE 6. Differentiation Power of Force Parameters in Box Trainers

Article	Participants N	Participants Type	Task	Dependent Measure	Results	p Value
Cundy et al.[17]	18	No, I, E	Peg transfer	- Mean relative nonzero force	No–I–E	0.006
				- Maximum force		0.020
				- Force magnitude		0.001
				- Force error		<0.001
			Suturing with intracorporeal knot	- Mean relative nonzero force		0.018
				- Maximum force		0.033
				- Force magnitude/force error		<0.001
Horeman et al.[18]	10	No, E	Needle-driving	- Max force	No–E	<0.017
				- Mean absolute nonzero force		<0.005
Horeman et al.[20,*]	32	No, E	Needlle-driving	- Mean absolute force/Standard deviation	No–E	0.001
				- Max absolute force		<0.001
				- Volume		0.022
				- Force Peak		<0.05
			Knot-tying	- Mean absolute force, Standard deviation, Volume		>0.05
				- Max absolute force		0.001
				- Force Peak		0.027
Horeman et al.[75]	42	No, I, E	Tissue attachment under traction	- Max absolute force	No–I	>0.05
					I–E	0.042
					No–E	<0.05
				- Mean absolute nonzero force	No–I/I–E/No–E	>0.05
				- Force volume	No–I	0.028
					I–E	0.034
					No–E	>0.05
				- Max force area	No–I/No–E	>0.05
					I–E	<0.05
				- STD force	No–I/I–E	>0.05
					No–E	<0.05
			Placement of silicone wire	- Max absolute force	No–I	>0.05
					I–E	0.002
					No–E	<0.001
				- Mean absolute nonzero force	No–I/I–E/No–E	>0.05
				- Force volume	No–I/I–E	<0.05
					No–E	>0.05
				- Max force area	No–I/No–E	>0.05
					I–E	0.036
				- STD force	No–I/I–E	>0.05
					No–E	0.017
Javaraman et al.[22]	20	No, E	Suturing	- Total force	No–E	>0.05
				- Grasping force		0.025
				- Torsion force		0.31
Trejos et al.[77]	30	No, E	Palpation	- Grasp mean, max, IQR	No–E	<0.05/>0.05**
				- Grasp integral, second, third derivative		<0.05/<0.05**
				- Grasp first derivative		<0.05/<0.05**
				- Cartesian forces mean, IQR		>0.05/>0.05**
				- Cartesian forces maximum, integral, first, second, third derivative		<0.05/<0.05**
			Cutting	- Grasp mean, maximum, IQR, integral, first, second, third derivative		>0.05
				- Cartesian forces mean, integral, second, third derivative		<0.05
			Tissue handling	- Grasp mean, IQR		>0.05/>0.05**
				- Grasp maximum, integral, first derivative		>0.05/<0.05**
				- Grasp second, third derivative		<0.05/<0.05**
				- Cartesian forces mean, maximum, IQR		>0.05/>0.05**
				- Cartesian forces integral, first, second, third derivative		<0.05/<0.05**

(continued)

TABLE 6 (*CONTINUED*)

Article	Participants		Task	Dependent Measure	Results
	N	Type			p Value
			Suturing	- Grasp mean, maximum, integral, first, second, third derivative	<0.05/<0.05**
				- Grasp IQR	>0.05/<0.05**
				- Cartesian forces mean, IQR	>0.05/<0.05**
				- Cartesian forces maximum, integral, first, second, third derivative	<0.05/<0.05**
			Knot tying	- Grasp mean, maximum, integral, first, second, third derivative	<0.05/<0.05**
				- Grasp IQR	>0.05/>0.05**
				- Cartesian forces mean, maximum, IQR, integral, first, second, third derivative	<0.05/<0.05**

p values in bold are significant.
No = novices; I = intermediates; E = experts.
*Only the most relevant dependent measures have been used.
**Left hand/right hand

A total of 7 studies have investigated visual force feedback systems.[10,12,20,24,78,83,84] These systems provide feedback either real time, during the task, or after having finished the task. Both methods have had positive effects on training results.[12,20,78,84] Real-time feedback can be provided as a constant feedback signal that is present throughout the entire task, but also in an intermittent manner. Smit et al. have compared constant visual feedback with band-with and fade-in visual feedback.[88] Band-with visual force feedback entails that feedback is presented only if a certain threshold is exceeded. With fade-in visual force feedback, the amount of feedback shown is dependent upon the skill-level of the participant. All types of real-time feedback improve tissue-handling skills with best result from a band-with presentation of visual force feedback.[88] The feedback signal used by Horeman et al. is a vector displaying the direction of the force and the amount of force used.[20,78] This lead to a 60% reduction of the used force and resulted in improved tissue-handling skills compared with visual feedback of the time progressed.[78] Besides real-time feedback, post-test feedback of force parameters has also been found to elicit a significant improvement of the interaction forces during the knot-tying face of suturing, whereas the effect of training without any feedback did not improve force use.[12] A simulator equipped with visual force feedback significantly improves precision and accuracy of force application by combining real-time visual feedback after practicing specifically designed tasks.[10,24,83]

Instead of visual feedback, Wottawa et al. have investigated the effect of enhanced tactile feedback. BTs already contain natural haptic feedbacks, therefore the tactile feedback signal consisted of an enhanced sensation transmitted to the handle grip using a specially designed laparoscopic grasper. The supplementary haptic feedback resulted in lower grasp force for novices. Experts used a comparable amount of grasp force in either setting.[81]

A safe grasp should not damage the tissue, but also avoid tissue slipping. To directly compare visual and tactual feedback, reaction times to tissue slippage have been measured. The results of this study showed that reaction times to upcoming tissue slippage were faster using tactile than visual feedback.[82] Further studies on this subject comparing different methods of force feedback are currently lacking.

Similar to studies examining the training effect of haptic feedback in VR trainers, the advantages of force feedback on learning or performance curves in BTs have been investigated. In BTs, force parameters can be used to create a learning curve.[17] Direct visual feedback of force interaction in box training was shown to significantly improve the learning curve of novices compared to training without visual feedback when provided in a real-time manner[78] and after finishing the exercise.[12]

Comparison of Haptic Feedback Between Simulators

Different simulators are used to train laparoscopic skills. Besides box- and VR trainers, a third type of simulator, an AR simulator, exists. In this type of system, the video screen of the simulator shows real images overlaid with graphical imagery to create an enhanced world around the user and to direct the user. It combines the natural haptic feedback of a box-trainer with the virtual surroundings and objective measures of performance of a VR simulator.[85] Only a very limited amount of studies has investigated AR simulators. One study has been found on discriminating power of AR simulators. It concludes that it is impossible to distinguish between novices and experts on an AR trainer based on force measurements alone during suturing.[21]

Lack of complete or natural haptic feedback is one of the most important characteristics distinguishing VR trainers from BTs. A comparison of these trainers could clarify the importance of (natural) haptic feedback for training laparoscopic skills. Several studies have aimed to compare the different types of haptic feedback employed by simulators.

A total of 7 studies have compared box and VR trainers.[2,52,55,67,86-88] The results of these studies are displayed in Table 7. A total of 3 studies found results favoring BTs.[2,55,86] The exerted force, time used and accuracy were significantly worse in the virtual environment.[86] Participants also performed better on a VR trainer after having practiced on a BT first, but not the other way around if tasks required force application[55] and laparoscopic suturing skills were not further improved by training on a VR trainer after having trained on a BT.[2] A total of 3 studies found comparable results for both types of trainers.[52,67,87] Madan and Frantzides found no significant differences in performance scores.[87] Balci et al. similarly report that objective structured assessment of technical skills scores are similar for both types of simulation trainers.[67] Both studies employ VR trainers without haptic feedback. Hiemstra et al. report that both a VR trainer supplied with additional kinematic interactions and BTs were found to improve economy of movement and speed when accomplishing a task demanding complex force application.[52] A study by Zhang et al. showed that performance scores after using a BT were significantly higher than those after using a VR trainer equipped with haptic feedback, but that the same VR trainer induced a steeper learning curve than a BT.[88]

AR trainers have been compared to VR trainers in 2 studies.[85,89] Performance after training on either an AR trainer or VR without haptic feedback did not differ significantly.[89] Comparison of the learning curves on a VR trainer and an AR trainer also did not indicate favorable results for either trainer.[89] An AR trainer, however, was considered a more realistic and better training tool and allowed more measurable parameters than a VR trainer without haptic feedback.[85]

DISCUSSION

Haptic, force, and tactile feedback are important concepts regarding laparoscopic surgery. The overall additional value of haptic feedback in VR trainers is contradictory. Haptic feedback does seem to have a small positive effect on training performances, which is most significant when performing more advanced tasks. Studies on learning curves show that simulators with haptic feedback accelerate ones learning and result in a steadier upward trend than those without haptic feedback, specifically at the beginning of training. Disadvantages of unnatural haptic feedback have furthermore been acknowledged such as the additional friction caused by a haptic interface device or unexpected movements due to model errors during instrument environment collisions. Moreover, the benefits of haptic feedback for novice surgeons in the skill acquisition phase of learning, whom simulation training is most often aimed at, is questionable. Comparing simulators with to simulators without haptic feedback, improvements are often minor for novices practicing basic skills. One of the reasons can be that creating perfect haptic feedback from a virtual environment seems difficult due to the required response time and operating frequency. Therefore it remains difficult to truly show the value of haptic feedback in complex laparoscopic tasks.

Concerning BTs, force parameters, especially when combined with motion parameters, are able to provide an objective rating of laparoscopic skills. Force feedback, moreover, improves training both when provided real time and post training. The possibilities of AR trainers, which provide natural haptic feedback as well as a more realistic environment, seem promising. The majority of the studies compared the effects of VR and BTs favor BTs over VR trainers. The results of AR and VR trainers were comparable.

When interpreting these results, several limitations must be considered. The most important limitation is the large amount of variability between the studies. Especially the studies concerning haptic interface devices are difficult to compare to each other. Studies use many different types of haptic interface devices, different simulators with tasks varying in difficulty, subjects, and outcome measures. The lack of universal outcome measures is especially conspicuous since it prevents direct comparison of the results of different studies. Second, several items are investigated in only a limited number of studies. The effect of force feedback on performance or learning curves for example is discussed in only 3 studies. As a result, conclusive evidence is missing. Finally, the one outcome measure that is very often used, time to complete a task, is often critically looked upon. It would promote working fast instead of conscientious and is especially unsuitable to evaluate beginners, who have not yet reached the autonomous learning phase.[77] This assumption is based on the theory of learning a skill by Fitts and Posner.[90] This theory subdivides the learning of a technical skill into 3 phases: the cognitive, assimilation, and autonomy phase. When a subject has not yet automated a certain skill, focussing

TABLE 7. Trainers With Natural Haptic Feedback Compared to VR Trainer with or Without Added Haptic Feedback

Article	Participants		Type of Simulator			Task	Outcome Measure		Conclusion
	N	Type	Box	VR					p Value
				Type	HF				
Balci et al.[67]	16	No	Box	LapSim	Y	Laparoscopic cyst decortication	OSATS	Respect to tissue	0.64
								Time and manipulation	0.50
								Instrumental experience	0.50
								Safety	1.00
								Assistant use	1.00
								Flow	0.23
								Accuracy	0.38
Bell and Cao[86]	10	No	Box	Handshake	Y	Probing	Time to detection	<0.001	
							Maximum force application	<0.001	
							Error in detection	0.007	
Botden et al.[2]	20	I	Box	SimSurgery	N	Suturing Knot tying	Summation of scores	Box vs control	0.298
								VR vs control	0.772
								Box vs VR	0.160
Chmarra et al.[89]	19	I	Box	SIMENDO	N	Balls task	Box + VR	Time/Path length/Depth perception	>0.05
						Ring task	Box + VR	Time/Path length/ Depth perception	>0.05
						Elastic band task	Box	Time/Path length/Depth perception	<0.001
							VR	Time, Path length L/Depth perception L	>0.05
								Path length R	<0.001
								Depth perception R	<0.002
Hiemstra et al.[52]	50	No	Box I / Box II*	VRI: SIMENDO/ VR II: SIMENDO**	I:N II:Y	Rubber band task	Time	VRI/ VRII/BoxI/Box II	<0.005
								Control	>0.05
							Total path length	VRI/Control	>0.05
								VR II/BoxI/BoxII	<0.005
							Motion in depth	VRI/Control	>0.05
								VRII/BoxII	<0.05
								BoxI	<0.01
Madan and Frantzides[87]	32	No	Box	MIST-VR	N	5 basic tasks (peg transfer/peg placement/pipe cleaner/probe through rings/rope)	Time/Error	>0.05	
Zhang et al.[88]	21	No, I, E	Box	VBLaST	Y	FLS	Total score	<0.001	

HF = haptic feedback; Box = box trainer; VR = virtual reality trainer; Y = yes; N = no.
*Box I: box trainer; Box II: box with kinematic interactions.
**VR I: SIMENDO, VR II: SIMENDO with kinematic interactions.

on fast times could lead to an increase of errors and result the acquirement of incorrect techniques.[91] Therefore, time measurement might not be an appropriate performance measure for novices and conclusions should not be based on time scores alone.

Despite these limitations, this review provides an elaborate overview of the literature, which includes a great number of studies on haptic and force sensing in simulation. Convincing evidence is provided concerning the benefits of force parameters, force sensing and force feedback. Reaching a univocal conclusion regarding haptic feedback in VR training, on the other hand, is difficult. Many different studies and contradicting results have been found throughout the literature concerning this subject. Interestingly, the emergence of robotic surgery could increase the popularity of VR trainers without haptic feedback. Since robots lack haptic feedback, VR trainers without a haptic interface device seem especially competent in teaching the skills necessary for this specific procedure.

For future research, it would be interesting to investigate the clinical impact of haptic and force feedback. This clinical impact is currently investigated on the box or VR trainer, instead of in the OR. Moreover, construct validity is often used to investigate the training ability of simulators. Construct validity shows that the simulator can be used to differentiate between different levels of experience. However, the ability to apply a skill in the operating room cannot be predicted with construct validity alone. To evaluate the effect of a simulator on OR performance a different method should be applied. For example, performance in the OR can be compared after training in different settings. This method has been previously applied to demonstrate the benefits of VR training.[92-96] Studies compared VR simulators without haptic or a comprehensive training curriculum comprising of box and VR training to no simulation training. Performance in the OR was significantly better after simulation training.[92-97] It would be interesting to apply this method to compare VR trainers with and without haptic feedback, BTs and AR trainers in future research. It would further be interesting to focus specifically on novice surgeons and evaluate the optimal training curriculum for residents at the beginning of their training.

CONCLUSION

The value of haptic and force feedback has been a subject of debate. Heterogeneity between and within studies describing the subject hinder decision-making. Haptic interface devices are required to endow VR simulators with haptic feedback. The surplus value of haptic feedback is inconclusive. Haptic feedback seems more important when more complex tasks are performed and can lead to an improved learning curve. Improvements, however, are only minor and less pronounced for novice surgeons. Force feedback in BTs has been shown to be beneficial both when provided real time and postpractice compared with BTs without force feedback. The use of force parameters, especially when combined with motion parameters has been reported to provide objective rating of laparoscopic skills.

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SUPPLEMENTARY INFORMATION

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jsurg.2018.06.008.