

The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review

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Abstract

Background Virtual reality (VR) as surgical training tool has become a state-of-the-art technique in training and teaching skills for minimally invasive surgery (MIS). Although intuitively appealing, the true benefits of haptic (VR training) platforms are unknown. Many questions about haptic feedback in the different areas of surgical skills (training) need to be answered before adding costly haptic feedback in VR simulation for MIS training. This study was designed to review the current status and value of haptic feedback in conventional and robot-assisted MIS and training by using virtual reality simulation.

Methods A systematic review of the literature was undertaken using PubMed and MEDLINE. The following search terms were used: *Haptic feedback OR Haptics OR Force feedback AND/OR Minimal Invasive Surgery AND/OR Minimal Access Surgery AND/OR Robotics AND/OR Robotic Surgery AND/OR Endoscopic Surgery AND/OR Virtual Reality AND/OR Simulation OR Surgical Training/ Education.*

Results The results were assessed according to level of evidence as reflected by the Oxford Centre of Evidence-based Medicine Levels of Evidence.

Conclusions In the current literature, no firm consensus exists on the importance of haptic feedback in performing minimally invasive surgery. Although the majority of the results show positive assessment of the benefits of force feedback, results are ambivalent and not unanimous on the

subject. Benefits are least disputed when related to surgery using robotics, because there is no haptic feedback in currently used robotics. The addition of haptics is believed to reduce surgical errors resulting from a lack of it, especially in knot tying. Little research has been performed in the area of robot-assisted endoscopic surgical training, but results seem promising. Concerning VR training, results indicate that haptic feedback is important during the early phase of psychomotor skill acquisition.

Keywords Haptic feedback · Minimal invasive surgery · Robotic surgery · Surgical training · Virtual reality

In every day life, the importance of the sense of touch is eminent. Recent studies have shown that loss of sense of touch can be catastrophic. Skilled actions, such as using tools, holding objects, or even plain walking, may become almost impossible upon losing the sense of touch [1]. Touch is the earliest sense developed in human embryology and is believed to be essential for good clinical practice [2, 3]. Therefore, the potential of haptic technology may not be underestimated for clinical specialities that rely on sensory input, such as minimally invasive surgery (MIS).

In surgery, haptic or force feedback refers to the sense of touch that a surgeon experiences—both consciously and unconsciously—while performing surgery. It is known that in MIS haptics are deprived compared with open surgery [4–7]. Haptics provide sensation to numerous surgical procedures, varying from structure to structure and depending on type of force applied, and relates to tissue damage, straightness of suturing, and task completion time [3, 8].

Within the various applications of MIS, a distinction can be made between conventional endoscopic surgery (CES)

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and robot-assisted endoscopic surgery (RAS). For CES the surgeon operates directly on the patient by using an endoscopic interface, whereas for RAS a computer-instrumented interface (surgical robot) is positioned between the surgeon and patient. Deprived haptic feedback, as experienced while performing CES, or a total lack of it, as experienced while performing RAS, may be a missing feature for the endoscopic surgeon [2, 9–11].

Next to ongoing developments in MIS, such as RAS, surgical training in MIS also has experienced rapid change. Virtual reality (VR) simulation is a computer-based application for MIS training. Beyond its infancy, VR simulation is integrated in many MIS training curricula throughout the world [9, 10, 12–16].

A comment that often is heard when discussing the integration of VR systems in MIS training curricula is the omission of haptic feedback in the many “basic” types of MIS–VR trainers. Again, no consensus is available on the importance of missing this type of feedback in training MIS surgery. Before validated implementation of costly haptic devices in basic and advanced MIS training can be accounted for, the importance of the lack of haptics in conventional CES and its omission in RAS should be assessed.

No clear consensus within the MIS performing community exists on the importance of deprived haptic feedback in MIS, related to MIS surgical outcome, and therefore in MIS training. We present a current overview of studies that assessed haptics in MIS and VR simulation and its possible implications. All studies were inventorized according to level of evidence as reflected by the Oxford Centre of Evidence-based Medicine Levels of Evidence [17].

Minimal invasive surgery: comparing conventional endoscopic surgery with robotic-assisted endoscopic surgery: The principle of MIS (e.g., operating through minimal incisions) is the same in CES as it is in RAS; however, there are some differences. The most obvious one is that in RAS a surgical robot is placed between the endoscopic surgical instruments and operating hands of the surgeon. This is referred to as “the master-slave principle.” The surgeon performs the movements while seated comfortably in a surgical operating console (master) and the movements are translated to the arms of a MIS robot (slave), thus executing them. The benefits commonly attributed to MIS, such as reduced morbidity, lower infection rates, less pain, faster recovery, and improved cosmesis, apply equally to CES and RAS [18–24].

A potential major drawback, comparing RAS to CES, is the absence of haptic feedback in RAS. In CES force feedback is experienced by the surgeon through the laparoscopic instrument handles, resulting from the interaction of the laparoscopic instruments tips with the tissue. In RAS, the latter end is formed by robotic arms, teleoperated by a console in which the surgeon performs his gestures.

As a result, no force feedback or haptics resulting from interaction with patient’s tissue are provided to the surgeon. In the literature, this is considered to be a (potential) major drawback because of the experienced difficulties in applying the correct amount of force on delicate tissue and suture materials, resulting in risk of slippage and tissue damage [4, 7, 25, 26].

Training MIS: Surgical training has become a subject of discussion and ongoing change. Receiving full training “on the job” is challenged by concerns for patient safety and resident working hour restrictions [6]. Therefore, alternative training methods must be provided to the resident within validated training curricula [6, 27]. These curricula may employ simple box trainers, inanimate and (live) animal models, and VR simulators [6].

Box trainers are well-known, inexpensive, and offer the experience of haptic feedback in contrast to nonhaptic-enhanced VR simulators. Animate models are logistically and ethically challenging. Virtual reality offers the possibility to train psychomotor skills using software, varying from simulating basic laparoscopic exercises to simple surgical tasks toward full operative procedures. By using repetitive VR training, a substantial part of the individual learning curve can be overcome before practicing on real patients [2, 14, 16]. One of the newest developments in VR training is VR training for RAS [11, 28, 29].

VR simulators offer value benefits in training compared with box trainers, in terms of repetitive training scenarios overcoming psychomotor learning curves, integration of didactic modalities, and objective assessment of outcome parameters.

Haptic feedback in MIS and training: Although non-haptic VR simulators have proven a transfer of skill to the operative room [9, 12–14, 30], the lack of haptic feedback is still considered as a potential drawback. The general opinion is that, in theory, realistic procedural simulations with haptic feedback lead to better performances, faster performance curves, and a high transfer of operative skill [18]. No consensus in literature, however, could be found about the importance of haptic feedback in VR simulation devices and the right manner of implementation.

To assess the importance of haptics, one first needs to know precisely what the limitations are in haptic sensations when performing or training MIS. What kind of haptic input—or how many different levels of force—does a MIS surgeon actually receive? And what type of force generated through haptic feedback is optimal? In what manner is the current loss of haptic feedback substituted to perform optimal MIS and VR training and are there alternatives? In which areas of VR training and in which way can haptic feedback be applied? And, most importantly, are results in CES or RAS improving by adding haptic feedback? Is an improvement in MIS outcome by adding haptics a stable

trait, or does the effect wear off when a surgeon becomes more experienced in performing a certain MIS procedure? These questions are addressed in the following paragraphs.

Haptic feedback in conventional endoscopic surgery

Present research focusing on haptic feedback and CES assesses aspects such as the decrease of haptic feedback in endoscopic surgery (due to the interposition of endoscopic instruments) and impaired sensoric feelings [4–6, 25, 31–33]. It is known that in surgery, sensoric stimuli are best felt through bare hands, followed by conventional surgical instruments, and lastly, by endoscopic instruments [32, 34, 35]. The amount of sensitivity loss measured when using endoscopic instrumentation instead of bare fingers varies between a factor of 8–20 [32]. Theoretically, however, using the instrument as a lever, the force generated from contact with an organ can be fed back to the surgeon 0.2–4.5 times the force generated by the organ-instrument interaction. This could imply a sensitivity enhancement, or at least a disturbance of haptic sensation, depending on the depth of instrument insertion into the body cavity [26]. Although the amount of force feedback is reduced, the interpretation of texture, shape, and tissue consistency are altered but present upon use of conventional endoscopic instruments [5, 20, 26, 35–38].

An endoscopic surgeon applies forces at the extremity of the instruments ranging from 0.5–12 Newton. These forces are translated to the instrument tips during endoscopic gestures, resulting into tissue handling ranging from 0.1–10.5 Newton [26, 38].

The main cause of disturbance of haptic sensations is frictional forces, which may exceed 3 Newton [26]. Frictional forces are forces caused by the friction between the instruments and the trocar. The fluctuation in frictional forces depends on the type of trocar used, the brand of the particular endoscopic instrument used, and the movement direction and velocity of the endoscopic instruments [39].

Frictional force may be reduced when enhancing the mechanical efficiency of the endoscopic instrument, for instance by lubricating the shaft of the instrument [39]. As a result, the amount of haptic feedback may be enhanced [32, 34]. The optimal mechanical efficiency depends on the specific task being performed [25, 38–43].

It seems that by combining several factors, such as visual feedback, haptic feedback, and endoscopic experience, performances of certain surgical tasks can be improved [5, 25]. Analyses performed by Tholey et al. show that no significant differences in performance occur when only one of these factors was present [5].

“Endoscopic experience” is a key factor in many of the assessed studies. The fact that experienced surgeons are

able to perform both CES and RAS successfully is an indication for some researchers that the possible positive effect of the addition of haptic feedback may be overestimated [25, 26]. It is suggested that haptic feedback should not be superimposed, because it may be subject to interfering forces. Furthermore, the amount of force feedback will differ according to, and depend on, the specific task being performed. High variance in interfering forces may worsen an endoscopic surgeon’s performance during tasks that require utmost precision [26, 39].

Patient safety is, as always in the field of medical research, an important aspect in the discussion on the importance of haptic feedback in MIS. Several authors assessed this area matter by conducting research in the occurrence of surgical error during CES, performed without force feedback. Video analysis of endoscopic procedures showed tissue slippage occurring during grasping actions, resulting in tissue damage, when haptic feedback was absent [25, 40, 44, 45].

A recent review by Westebring-van der Putten et al. supports the concept of using haptic feedback in MIS. It is stated that the concept is indeed promising, although rare in actual presence. Surgeons could possibly benefit from additional feedback, but there is still much to learn about the specifics and advantages of included force feedback when it comes to preventing surgical errors [46]. The results are summarized in Table 1.

Haptic feedback in robot-assisted endoscopic surgery

In RAS, lack of force feedback may prologue operative times and learning curves, and increase the risk of surgical errors [38, 47–50]. Bethea et al. reported that even experienced surgeons training with RAS often tear apart sutures and damage delicate tissues [7]. This is attributed to the exertion of excessive force by the surgeon during his performance, because any form of force feedback is absent. In a study investigating the effects of haptic feedback on blunt dissection using a telerobotic system, Wagner et al. found that the absence of haptic feedback increased errors causing tissue damage by a mere factor of 3 [51].

The loss of force feedback in RAS compared with CES may be balanced partly by the restoration of three-dimensional vision. This is important because in the current operative situation, a surgeon must foremost rely on the visual deformation of tissue when performing MIS in general, and even more so in performing RAS [7, 51]. Several studies report direct improvements in performance times, accuracy, and decrease in error rates for both inexperienced and experienced endoscopic surgeons, when using three-dimensional vision instead of conventional two-dimensional vision in MIS [52–54].

Table 1 Current status of haptic feedback in CES

Subject	Study objective(s)	Conclusion	Level of evidence ^a	Literature reference
<i>Instrumentation</i>				
Consequences of interposition of endoscopic instruments		Haptic feedback is decreased in conventional endoscopic surgery	3b/4	[4–6] [25, 31–33]
		Due to an interaction force of the instrument tips contacting organs or tissue, a certain amount of haptic feedback remains		
Quantification of haptics	Evaluate feedback quality laparoscopic dissectors	Haptic feedback is best felt through: 1. Bare hands 2. Instruments for open surgery 3. Endoscopic instruments	3b	[32] [26, 36, 37]
	Determine ability of novice surgeons to interpret haptic feedback	There is a 8–20× sensitivity loss when using endoscopic instrument instead of bare fingers.		
	Characterize laparoscopic gestures	Using the instrument as a lever, theoretically, the force generated from contact with an organ can be fed back to the surgeon 0.2–4.5 times the force generated by organ-instrument interaction		
	Analyze strain and working volume of existing endoscopic instruments	The forces applied at the extremity of the instrument by the surgeon during a laparoscopic gesture range from 0.5–1	3b	[38]
	Characterize laparoscopic gestures and quantitative measurement of interactions between organs and the instrument	The translated force exerted at the instrument tips range from 0.4–10.5 N	3b	[26]
	Investigate the dynamic changes in friction for various trocars at different instrument velocities	Frictional forces of endoscopic instruments with the trocar can exceed 3 N	3b	[39]
	Determine the ability of experienced surgeons to interpret haptic feedback	High variance in interfering forces may worsen an endoscopic surgeon's performance during tasks requiring utmost precision		
		Interpretation of the texture, shape, and consistency of objects can be performed using endoscopic instruments. In some situations, endoscopic instruments seem to amplify the haptic information available	3b	[37]
	Determine the ability of novice surgeons to interpret haptic feedback	While endoscopic instruments change the information available to the surgeon, interpretation of the texture, shape, and consistency of objects can be performed	3b	[37]

Table 1 continued

Subject	Study objective(s)	Conclusion	Level of evidence ^a	Literature reference
Mechanical efficiency	Determine influences of visual feedback, force feedback, and the experience of the surgeon, both on grasping tissue and on holding tissue	The exerted pinch force on the tissue was not influenced by the mechanical efficiency of the forceps	3b	[25]
	Evaluate the feedback quality of commercially available reusable and disposable laparoscopic dissectors	Enhancing instrumental mechanical efficiency enhances haptic feedback	3b	[32] [34]
	Gaining tactile and kinesthetic information for new user interfaces in MIS			
	Developing new technologies to rectify loss of sensory feedback	Optimal mechanical efficiency of forceps depends on specific task being performed.	3b	[40–43]
<i>Vision</i>				
Influence of vision on surgical performance	Evaluate the role of force feedback with applications to minimally invasive surgery	Vision and haptic feedback combined improve tissue consistency determination	3b	[5]
	Determination of influences of visual feedback, force feedback, and the experience of the surgeon, both on grasping tissue and on holding tissue	The exerted pinch force on tissue is not influenced by visual feedback alone	3b	[25]
<i>Miscellaneous</i>				
Haptic feedback is not essential when performing MIS	Gaining tactile and kinesthetic information for new user interfaces in MIS	Experienced surgeons are able to perform both CES and RAS without complications, without force feedback	3b	[25] [39] [60]
	Determination of influences of visual feedback, force feedback, and the experience of the surgeon, both on grasping tissue and on holding tissue	Force feedback, visual feedback, and laparoscopic experience provided to be less important than initially expected in the particular task of holding tissue		
	To characterize laparoscopic gestures and quantitative measurement of the various interactions between organs and the instrument	The optimal mechanical efficiency of laparoscopic forceps depends on the specific tasks performed with the forceps		
	Determination of influences of visual feedback, force feedback, and the experience of the surgeon, both on grasping tissue and on holding tissue	Haptic feedback should not be taken into account because it is subject to other forces	3b	[26]
Absence of haptic feedback causes slippage and tissue damage	To investigate the effectiveness of grasping and the duration of tissue-clamping using laparoscopic forceps	7% tissue slippage in grasping actions Pinch force necessary to prevent slippage was on average 3 N 62% of grasping actions were successful 7–10% of clamping actions were repeated actions. Tissue slippage occurred in 7–17%	3b	[37] [45]
		Video analysis showed that applying the correct amount of force when grasping tissue without force feedback leads to slippage and tissue damage	3b	[40] [44]

All studies were conducted as individual case–control study

^a Based on the guidelines of the Oxford Centre of Evidence-based Medicine Levels of Evidence [17]

Some study results suggest that other forms of feedback may prove a successful compensation for loss of force feedback, for example, visual cues indicating the visual deformation of tissue. This is a suitable substitution if the surgeon is able to correlate the forces applied and tissue deflection on a good internal model of tissue consistency [7, 51]. Bethea et al. demonstrated that during robotic knot tying, greater and more consistent tension may be applied to suture materials when haptic feedback is applied [7]. Haptic feedback was supplied in the form of a visual color bar scale, which changed color when different forces were applied. In the literature, this concept often is called “visual haptics.”

The use of visual and auditory feedback of force levels combined has been found to improve consistency of applied forces during knot tying, even more consistent than with those being hand-tied. In a preliminary study by Okamura et al., auditory feedback as sensory substitution was tested and proven a success [55]. The accompanying additional noises, added to sounds already present during operation, such as those made by hemodynamic/pulse oximetry monitors, may undesirably interfere with the surgical process [7, 53].

Addition of force feedback in MIS would enable surgeons to “feel” tissue characteristics, identify pathologic tissue, and tie sutures with appropriate tension, as in open surgery [54]. In the past, various system technologies, actuators, and forms of sensory substitution have been tested to accomplish an alternative for the missing tactile information, to estimate the amount of force applied [56]. Tavakoli et al. successfully describe a robotic sensory end-effector [57]. Besides the incorporation of haptic feedback, authors suggest the end-effector to be of use in evaluating skills and monitor learning curves in RAS training.

A new development in the area of robotic sensory end-effector technology is pneumatic tactile displays [56]. Preliminary human perceptual tests of King et al. with implemented pneumatic balloon actuators provide effective force feedback to the human index finger [55]. So far, the implementation of force sensors has not been commercially successful, despite the fact that there are currently several robotic surgical systems on the market [4, 58]. Reasons for this are unclear; (mass) production and research of the above-mentioned sensory end-effector technologies are probably still in an experimental phase. The results are summarized in Table 2.

Most studies conducted regarding CES and the possible influence of haptic feedback are case–control-type surveys and literary reviews. Although the number of studies conducted concerning RAS and haptic feedback is scarce compared with the number of studies concerning CES and force feedback, the level of evidence and results are alike. Study populations are small and do not involve multiple

study centers. Therefore, they can be classified as having a level of evidence of 4 or 3b at most, according to the guidelines of the Oxford Centre of Evidence-based Medicine Levels of Evidence [17].

Haptic feedback in VR (MIS) training

Application of haptic feedback in virtual reality training

According to Fager et al., haptics using VR simulation can be implicated in two distinct areas: medical training and clinical practice [2]. Overviews of MIS-haptic training possibilities, potential VR implications, and current VR simulators available with haptic feedback are shown in Tables 3, 4, 5 [2, 6, 59].

VR simulation with haptic feedback

Currently, study results indicative for a true value of haptic feedback in VR simulation are low. Many conclusions on the subject are drawn from study results primarily based on the possible importance of haptic feedback in MIS, not so much in VR training [5, 25, 33, 60, 61].

The majority of studies support the idea that haptic feedback should be implemented onto VR simulators [5, 33, 62]. Various forms of haptic feedback can only be felt up to four or five different levels—important information for simulator calibration [5]. Some results suggest that the addition of haptic feedback in an early training phase may improve the trainee’s performance, by enhancing the trainee’s sensoric perception capabilities and thus facilitating transfer of skill from simulation to the operating room [31, 33, 63]. It is suggested that force feedback is a must for VR simulators if tissue consistency information is to be delivered [33]. This is supported by the study results of Chamarra et al. [64]. This group warns about a negative learning effect that may occur when performing tasks where pulling and pushing forces play a major role on surgical task outcome, after being trained using VR systems without realistic haptics. Their recommendation is to use VR trainers solely to overcome hand-eye coordination problems and continue training using a classic box trainer in which training set-ups allow for realistic pulling and pushing forces.

Results of studies on the frictional forces of various trocars used in endoscopic surgery further emphasize the importance of the realism of implemented force feedback. Implementation of realistic haptic devices applicable to VR simulators seems to be difficult. One first needs to know what type of haptic feedback in combination with disturbing frictional forces is optimal, realistic, and applicable to VR simulation [26, 39].

Table 2 Current status of haptic feedback in RAS

Subject	Study purpose	Conclusion	Level of evidence ^a	Literature reference
Consequences				
Influence on operative times of absence of haptic feedback	Compare robotically and traditionally performed laparoscopic colorectal surgery	Absence of haptic feedback prolongs operative times in robot-assisted colorectal surgery	1b	[47]
	Trial of robot-assisted vs. laparoscopic Nissen fundoplication	Absence of haptic feedback prolongs operative times in robot-assisted Nissen fundoplication	1b	[48]
	Study the feasibility of the Nissen procedure using the da Vinci robot and evaluate the benefits and costs new technique compared with the conventional laparoscopic approach	Absence of haptic feedback prolongs operative times in robot-assisted cholecystectomy	1b	[49]
	Evaluate the efficiency and feasibility of robotically assisted cholecystectomy compared with standard laparoscopic cholecystectomy.	Absence of haptic feedback prolongs operative times in robot-assisted coronary artery bypass surgery	1b	[50]
Influence on surgical performance of absence of haptic feedback	Does haptic feedback, in the form of sensory substitution, facilitate the performance of surgical knot tying?	Haptic feedback increases consistency, precision, and performance in robotic knot tying	3b	[7]
	Role of force feedback in blunt, surgical, dissection	Without haptic feedback, sutures and tissues are torn, even by experienced surgeons Absence of force feedback increased the number of errors that damage tissue by factor 3	3b	[51]
Possible solutions				
Alternative forms of feedback	Does haptic feedback, in the form of sensory substitution, facilitate the performance of surgical knot tying?	Visual sensory substitution helps to apply more consistent, precise, and greater tensions to fine suture materials without breakage during RAS	3b	[7] [51]
	Overview of research in dexterous manipulation	Audio feedback is proven as a valuable sensory substitution	4	[55]
Addition of haptic feedback	Test pneumatic haptic feedback actuator array, suitable for mounting on surgical robotic tools	Pneumatic balloon-based actuation is a viable solution for generating haptic feedback in RAS	3b	[55] [56]

Studies were conducted as literary review, individual case–control study, prospective randomized trial, or randomized clinical trial

^a Based on the guidelines of the Oxford Centre of Evidence-based Medicine Levels of Evidence [17]

Table 3 MIS training devices and presence haptic feedback

Training device	Haptic feedback?
Box trainers	Yes
Animal models	Yes
VR training without haptic feedback	No
VR training with haptic feedback	Yes
Augmented reality training (AR)*	Yes

Occasionally, the value of adding haptic feedback in VR training is discussed as experienced surgeons have long performed both CES and RAS, without force feedback, without complications [25, 60].

Specific RAS training with haptic feedback

Specific RAS-training methods are still in its infancy, and few study results are known on the subject. A preliminary

Table 4 Application of haptic feedback in VR training

Medical training	Clinical practice
Procedural training (e.g., broncho-/colono-/gastroscopy, cricothyroidotomy, laparoscopic cholecystectomy, vascular interventions)	Surgery/treatment planning (e.g., testing of multiple reconfigurations for reconstructive surgery)
Anatomy learning (e.g., palpation and dissection)	Robotic surgery Diagnostics (e.g., medical image interpretation, invasive procedures, tumor diagnostics)

Table 5 Currently available VR trainers with haptic feedback appliance

VR trainer	Manufacturer
Procedicus MIST	Mentice (www.mentice.com)
Lapsim Basic Skills/Dissection/ Gyn	Surgical Science (www.surgical-science.com)
Reachin Laparoscopic Trainer	Reachin Technologies (www.reachin.se)
Virtual Endoscopic Surgery Trainer	Select IT VEST Systems (www.select-it.de)

study by Jacobs et al. demonstrated the potential value and impact of training RAS with a combination of haptic and visual feedback [65]. Results indicate improved training performances with applied haptic feedback as to task completion time, accuracy, and number of errors made compared with task performances with only visual feedback, suggesting a complete altering of RAS training in the future.

Recapitulating the results of forementioned studies, as with MIS, there is no absolute consensus on the importance of haptic feedback in (VR) training for MIS. To date, little is known on the subject. Preliminary studies indicate a positive result of the addition of haptic feedback to VR simulation for MIS and RAS training regarding training performance. It is believed that the degree of realism of implemented haptic feedback is to play a crucial role in task-specific VR training. In general, studies do not qualify above a level of evidence 3b [17]. A summary of the known study results concerning haptic feedback in VR training is displayed in Table 6.

Discussion

Reflected in literature are many studies assessing the characteristics, possible benefits, and drawbacks of haptic

Table 6 Current status of haptic feedback in VR simulation and RAS training

Subject	Study purpose	Conclusion	Level of evidence ^a	Literature reference
<i>Miscellaneous</i>	Evaluate the role of force feedback with applications to minimally invasive surgery	Haptic feedback is essential to deliver tissue consistency Various forms of haptic feedback can only be felt up to 4 or 5 different levels	3b	[5]
	Does addition of haptics improve performance in surgical training?	Early exposure to haptic feedback enhances performance in surgical simulator training Sensory stimuli are more important than visual cues. During early stages of training, sensory perception capabilities improve	3b	[31] [33]
	Study perception of tissue consistency	VR simulators need haptic devices with force feedback capability if tissue consistency information is to be delivered	3b	[33] [64]
	Determine whether force feedback influences movements of instruments	Negative learning effect may occur when performing tasks where pulling and pushing forces play a role in VR systems without haptics		
	Characterize laparoscopic gestures and quantitative measurement of the various interactions between organs and instrument	The question of whether to equip a trainee's simulator with a force feedback system remains open	3b	[26]
	Description of a framework that includes most of the important aspects of haptics in minimally invasive surgical simulation and training	Haptic feedback involves touching, feeling, and manipulating organs through instruments and should be implemented in MIS and VR training	3b	[61]
	Current status in acquisition and assessment of surgical skills by using VR simulators	Haptic feedback is the most important factor in learning surgical dexterous skills	3b	[62]
	Demonstrate the potential value of haptic and visual feedback combined in RAS training	Compared with traditional use of only visual feedback, a combination of haptic and visual feedback improves training accuracy, fastens task completion times, and decreases number of errors	3b	[65]

Studies were conducted as literary review or individual case–control study

^a Based on the guidelines of the Oxford Centre of Evidence-based Medicine Levels of Evidence [17]

feedback in relation to the various forms of minimally invasive surgery, conventional endoscopic surgery, robotic-assisted surgery, and MIS training. In an overview of the results, one could state that there is no clear and absolute consensus found on the benefits of haptic feedback in MIS and MIS training. However, scrutinizing the results in more detail, the authors feel that one's opinion is not likely to be firm.

Upon assessing the evidence, authors assessed both the interarticle consensus on the respective topics and the extent to which evidence seemed to be useful in answering the questions annotated in the introduction of this article.

The cause of haptic limitations in performing MIS is well assessed and caused by the interposition of endoscopic instruments. Despite this alteration in haptics, researchers agree that interpretation of texture, shape, and tissue consistency is possible in current CES, but not in current RAS. Studies assessing quantification of sensitivity loss report variation in received haptic feedback, depending on frictional forces and specific tasks being performed. Exact quantification of haptic alteration is not unanimous, but results so far are in concordance.

Then, what kind of haptic input—or how many different levels of force—does a CES surgeon actually receive? And what type of force generated through haptic feedback is optimal? Reports on generated forces during endoscopic gestures range from 0.1–12 Newton, translating into a surgical interpretation of only up to four or five different levels of haptic feedback in the operative situation. This is important information when attempting to apply haptics into VR surgical simulation and in calibrating simulators. The optimal, most realistic type of haptic feedback for possible implementation remains unclear to authors. Both the ideal type of generated force feedback as well as the ideal mechanical efficiency of endoscopic instruments depends on the specific task being performed.

To perform optimal MIS and VR training, one must first and foremost rely on the visual deformation of tissue when haptics are absent, even more so in RAS than in CES. This states the obvious, because haptics are completely lacking in current RAS. Further results, which indicate the huge value of three-dimensional vision restoration that occurs in RAS, also seem logical. Multiple studies report direct improvements in performance times and accuracy, and a decrease in error rate for both inexperienced and experienced endoscopic surgeons after three-dimensional restoration in MIS. Suitable substitutions for current loss of haptics have possibly been found in visual cues and auditory feedback. One might view these substitutions as a type of haptic feedback. Force sensors need to be implemented into instruments used to report exerted forces through visual color bars or some sort of auditory feedback when handling tissue.

In which areas of VR training and in which way can haptic feedback be applied? The fields of application could

possibly be both medical training and clinical practice. Little is known about the optimal and most realistic type of haptic feedback to be implemented into VR simulators. The realism of the haptic feedback will have a decisive role in the possible success of implementation.

The key question for future research on the matter should be: are results in CES or RAS improved by adding haptic feedback? For now, besides reduced operative times, the small amount of results indicating a favorable effect of haptic feedback on surgical performance and patient safety are merely obtained by individual case-control studies (level of evidence, 3b–4) [17]. Furthermore, research populations—consisting of surgeons and residents—were, in general, small (<20 study subjects) and not multicentered.

Whether possible improvement in MIS outcome by adding haptics is a stable trait remains unclear. Throughout literature, no results were found, pointing out indifferent influences of possible addition of force feedback on operative parameters, let alone negative effects. The few opposing remarks made on haptic feedback are primarily based on the thesis that experienced surgeons have long been able to perform MIS without force feedback without complication. This seems to be the main reason that results are heterogenous, and although a favorable opinion on the benefits of haptic feedback is common, interarticle consensus cannot be fully obtained.

Conclusions and recommendations

Although information on haptic feedback regarding MIS and especially MIS VR training is rare throughout the literature, study results are indicative toward a positive consensus on the benefits of adding haptic feedback to MIS (-trainers). Interarticle consensus is, however, neither absolute nor firm. Objective, clinical end parameters of significance have not yet been established. The general level of evidence found for study results is 3b, according to the guidelines of the Oxford Centre of Evidence-based Medicine Levels of Evidence. As in all fields of health care and medicine, due to technological innovations, the current rate of haptic device developments and clinical MIS applications is high, and studies are expected to emerge rapidly on the subject.

The majority of studies report benefits when adding force feedback to MIS devices and, moreover, indicate drawbacks when haptic feedback is absent. The degree of realism of implemented haptic feedback related to the particular task that is being trained will have a key role in the future. Benefits are least disputed in the area of robotic surgery, because haptic feedback is absent in robotic surgical devices. Nevertheless, the addition of haptics is believed to reduce surgical errors and potentially increase patient safety.

Regarding various forms of MIS, randomized and controlled trials that assess instruments with and without force feedback need to be studied. Regarding VR trainers, randomized and controlled trials that add haptics to VR under similar conditions are needed to establish the true value of such costly equipment in MIS training.

More objective study results based on valid end parameters—useful for assessing clinical relevance—need to be obtained to truly state the value of haptic feedback. For now, the question of the true value of haptic feedback in MIS training devices remains unanswered.

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References

- Robles de la Torre G (2006) The importance of the sense of touch in virtual and real environments. *IEEE Multimedia*
- Fager PJ (2004) The use of haptics in medical application. *Int J Med Robotics Comput Assisted Surg* 1:36–42
- Dunkin B, Adrales GL, Apelgren K, Mellinger JD (2007) Surgical simulation: a current review. *Surg Endosc* 21:357–366
- Lanfranco AR, Castellanos AE, Desai JP, Meyers WC (2004) Robotic surgery: a current perspective. *Ann Surg* 239:14–21
- Tholey G, Desai JP, Castellanos AE (2005) Force feedback plays a significant role in minimally invasive surgery: results and analysis. *Ann Surg* 241:102–109
- Roberts KE, Bell RL, Duffy AJ (2006) Evolution of surgical skills training. *World J Gastroenterol* 12:3219–3224
- Bethea BT, Okamura AM, Kitagawa M, Fitton TP, Cattaneo SM, Gott VL, Baumgartner WA, Yuh DD (2004) Application of haptic feedback to robotic surgery. *J Laparoendosc Adv Surg Tech A* 14:191–195
- Moody L, Baber C, Arvanitis TN (2002) Objective surgical performance evaluation based on haptic feedback. *Stud Health Technol Inform* 85:304–310
- Grantcharov TP, Kristiansen VB, Bendix J, Bardram L, Rosenberg J, Funch-Jensen P (2004) Randomized clinical trial of virtual reality simulation for laparoscopic skills training. *Br J Surg* 91:146–150
- Aggarwal R, Grantcharov T, Moorthy K, Hance J, Darzi A (2006) A competency-based virtual reality training curriculum for the acquisition of laparoscopic psychomotor skill. *Am J Surg* 191:128–133
- Halvorsen FH, Elle OJ, Dalinin VV, Mork BE, Sorhus V, Rotnes JS et al (2006) Virtual reality simulator training equals mechanical robotic training in improving robot-assisted basic suturing skills. *Surg Endosc* 20:1565–1569
- Lathan CE, Tracey MR, Sebrechts MM, Clawson DM, Higgins GA (2002) Using virtual environments as training simulators: measuring transfer. In: Stanney KM (ed) *Handbook of virtual environments: design, implementation and applications*. Lawrence Erlbaum Associates, Mahwah, pp 414–434
- Seymour NE, Gallagher AG, Roman SA, O'Brien MK, Bansal VK, Andersen DK, Satava RM (2002) Virtual reality training improves operating room performance: results of a randomized, double-blinded study. *Ann Surg* 236:458–464
- Schijven MP, Jakimowicz JJ, Broeders IAMJ, Tseng LNL (2005) The Eindhoven laparoscopic cholecystectomy training course—improving operating room performance using virtual reality training. *Surg Endosc* 19:1220–1226
- Aggarwal R, Tully A, Grantcharov T, Larsen CR, Miskry T, Farthing A, Darzi A (2007) Virtual reality simulation training can improve technical skills during laparoscopic salpingectomy for ectopic pregnancy. *BJOG* 114:656
- Aggarwal R, Grantcharov TP, Eriksen JR, Blirup D, Kristiansen VB, Funch-Jensen P, Darzi A (2006) An evidence-based virtual reality training program for novice laparoscopic surgeons. *Ann Surg* 244:310–314
- Philips B, Ball C, Sackett D, Badenoch D, Straus S, Haynes B, Dawes M (2001) *Oxford Centre for Evidence-based Medicine Levels of Evidence*
- Keus F, De Jong JA, Gooszen HG, Van Laarhoven CJ (2006) Small-incision versus open cholecystectomy for patients with symptomatic cholecystolithiasis. *Cochrane Database Syst Rev* 4:CD004788
- Keus F, De Jong JA, Gooszen HG, Van Laarhoven CJ (2006) Laparoscopic versus open cholecystectomy for patients with symptomatic cholecystolithiasis. *Cochrane Database Syst Rev* 4:CD006231
- Barczynski M, Cichon S, Konturek A, Cichon W (2006) Minimally invasive video-assisted parathyroidectomy versus open minimally invasive parathyroidectomy for a solitary parathyroid adenoma: a prospective, randomized, blinded trial. *World J Surg* 30:721–731
- Sekhar N, Torquati A, Youssef Y, Wright JK, Richards WO (2007) A comparison of 399 open and 568 laparoscopic gastric bypasses performed during a 4-year period. *Surg Endosc* 21:665–668
- Kluivers KB, Hendriks JC, Mol BW, Bongers MY, Bremer GL, De Vet HC, Vierhout ME, Brolmann HA (2007) Quality of life and surgical outcome after total laparoscopic hysterectomy versus total abdominal hysterectomy for benign disease: a randomized, controlled trial. *J Minim Invasive Gynecol* 14:145–152
- Staudacher C, Vignali A, Saverio DP, Elena O, Andrea T (2007) Laparoscopic vs. open total mesorectal excision in unselected patients with rectal cancer: impact on early outcome. *Dis Colon Rectum* 50:1324–1331
- Tong DK, Law WL (2007) Laparoscopic versus open right hemicolectomy for carcinoma of the colon. *JSLS* 11:76–80
- Heijnsdijk EAM, Pasdeloup A, van der Pijn AJ, Dankelman J, Gouma DJ (2004) The influence of force feedback and visual feedback in grasping tissue laparoscopically. *Surg Endosc* 18:980–985
- Picod G, Jambon AC, Vinatier D, Dubois P (2005) What can the operator actually feel when performing a laparoscopy? *Surg Endosc* 19:95–100
- Bridges M, Diamond DL (1999) The financial impact of teaching surgical residents in the operating room. *Am J Surg* 177:28–32
- Fiedler MJ, Chen SJ, Judkins TN, Oleynikov D, Stergiou N (2007) Virtual reality for robotic laparoscopic surgical training. *Stud Health Technol Inform* 125:127–129
- Albani JM, Lee DI (2007) Virtual reality-assisted robotic surgery simulation. *J Endourol* 21:285–287
- Satava RM (1993) Virtual reality surgical simulator: the first steps. *Surg Endosc* 7:203–205
- Ström P, Hedman L, Särna L, Kjellin A, Wredmark T, Felländer-Tsai L (2006) Early exposure to haptic feedback enhances performance in surgical simulator training: a prospective randomized crossover study in surgical residents. *Surg Endosc* 20:1383–1388
- den Boer KT, Herder JL, Sjoerdsma W, Meijer DW, Gouma DJ, Stassen HG (1999) Sensitivity of laparoscopic dissectors: what can you feel? *Surg Endosc* 13:869–873
- Lamata P, Gomez EJ, Sanchez-Margallo FM, Lamata F, del Pozo F, Usón J (2006) Tissue consistency perception in laparoscopy to

- define the level of fidelity in virtual reality simulation. *Surg Endosc* 20:1368–1375
34. Lehnert M, Richter B, Beyer PA, Heller K (2006) A prospective study comparing operative time in conventional laparoscopic and robotically assisted Thal semifundoplication in children. *J Pediatr Surg* 41:1392–1396
 35. Rosen J, Hannaford B, MacFarlane MP, Sinanan MN (1999) Force controlled and teleoperated endoscopic grasper for minimally invasive surgery—experimental performance evaluation. *IEEE Trans Biomed Eng* 46:1212–1221
 36. Bholat OS, Haluck RS, Murray WB, Gorman PJ, Krummel TM (1999) Tactile feedback is present during minimally invasive surgery. *J Am Coll Surg* 198:349–355
 37. Bholat OS, Halluck RS, Kutz RH, Gorman PJ, Krummel TM (1999) Defining the role of haptic feedback in minimally invasive surgery. *Stud Health Technol Inform* 62:62–66
 38. Toledo L, Gossot D, Fritsch S, Revillon Y, Reboulet C (1999) Study of sustained forces and the working space of endoscopic surgery instruments. *Ann Chir* 53:587–597
 39. van den Dobbelsteen JJ, Schooleman A, Dankelman J (2006) Friction dynamics of trocars. *Surg Endosc* 21:1338–1343
 40. Van der Peijl AJ, Herder JL (2001) Development of 5-mm trocar laparoscopic forceps with mechanical force feedback. *Proceedings of the Design Engineering Technical Conferences 2001, American Society of Mechanical Engineers*, 3–12 September 2001, DETC 01, ASME Conference, Pittsburgh, PA, USA
 41. Balázs M, Feussner H, Hirzinger G, Omote K, Ungeheuer A (1998) A new tool for minor-access surgery: replacing mechanical joints in laparoscopic forceps with elastic beams for improved pressure control and sensitivity. *IEEE Eng Med Biol* 17:45–48
 42. Herder JL, Horward MJ, Sjoerdsma W (1997) A laparoscopic grasper with force perception. *Minim Invasive Ther Allied Technol* 6:279–286
 43. Howe RD, Peine WJ, Kontarinis DA, Son JS (1995) Remote palpation technology. *IEEE Eng Med Biol* 14:318–323
 44. Sjoerdsma W, Herder JL, Horward MJ, Jansen A, Bannenberg JJG, Grimbergen CA (1997) Force transmission of laparoscopic grasping instruments. *Minim Invasive Ther Allied Technol* 6:274–278
 45. Heijnsdijk EAM, Dankelman J, Gouma DJ (2002) Effectiveness of grasping and duration of clamping using laparoscopic graspers. *Surg Endosc* 16:1329–1331
 46. Westebring-van der Putten EP, Goossens RH, Jakimowicz JJ, Dankelman J (2008) Haptics in minimally invasive surgery—a review. *Minim Invasive Ther Allied Technol* 17:3–16
 47. Delaney CP, Lynch AC, Senagore AJ, Fazio VW (2003) Comparison of robotically performed and traditional laparoscopic colorectal surger. *Dis Colon Rectum* 46:1633–1639
 48. Morino M, Pellegrino L, Giaccone C, Garrone C, Rebecchi F (2006) Randomized clinical trial of robot-assisted versus laparoscopic Nissen fundoplication. *Br J Surg* 93:553–558
 49. Nakadi IE, Melot C, Closset J, DeMoor V, Betroune K, Feron P, Lingier P, Gelin M (2006) Evaluation of da Vinci Nissen fundoplication clinical results and cost minimization. *World J Surg* 30:1050–1054
 50. Kornprat P, Werkgartner G, Cerwenka H, Bacher H, El-Shabrawi A, Rehak P, Mischinger HJ (2006) Prospective study comparing standard and robotically assisted laparoscopic cholecystectomy. *Langenbechks Arch Surg* 391:216–221
 51. Wagner CR, Soupoulos N, Howe RD (2002) The role of force feedback in surgery: analysis of blunt dissection. 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS), 24–28 March 2002, pp 68–74
 52. Badani KK, Bhandari K, Tewari A, Menon M (2005) Comparison of two-dimensional and three-dimensional suturing: is there a difference in a robotic surgery setting? *J Endourol* 19:1212–1215
 53. Falk V, Mintz D, Grünenfelder J, Fann JJ, Burdon TA (2001) Influence of three-dimensional vision on surgical telemanipulator performance. *Surg Endosc* 15:1282–1288
 54. Byrn JC, Schluender S, Divino CM, Conrad J, Gurland B, Shlasko E, Szold A (2007) Three-dimensional imaging improves surgical performance for both novice and experienced operators using the da Vinci Robot System. *Am J Surg* 193:519–522
 55. Okamura A, Smaby N, Cutkosky M (2000) An overview of dexterous manipulation. *ICRA* 1:255–262
 56. King CH, Higa AT, Culjat MO, Han SH, Bisley JW, Carman GP, Dutson E, Grundfest WS (2007) A pneumatic haptic feedback actuator array for robotic surgery of simulation. *Stud Health Technol Inform* 125:217–222
 57. Tavakoli M, Patel RV, Moallem M (2005) Haptic interaction in robot-assisted endoscopic surgery: a sensorized end-effector. *Int J Med Robot* 1:53–63
 58. Ruurda JP, ThJMV Van Vroonhoven, Broeders IAMJ (2002) Robot-assisted surgical systems: a new era in laparoscopic surgery. *Ann R Coll Surg Engl* 84:223–226
 59. Botden SM, Buzink SN, Schijven MP, Jakimowicz JJ (2007) Augmented versus virtual reality laparoscopic simulation: what is the difference? A comparison of the ProMIS Augmented Reality Laparoscopic Simulator versus LapSim Virtual Reality Laparoscopic Simulator. *World J Surg* 31:764–772
 60. Wilson MS, Middlebrook A, Sutton C, Stone R, McCloy RF (1997) MIST VR: a virtual reality trainer for laparoscopic surgery assesses performance. *Ann R Coll Surg Engl* 79:403–440
 61. Basdogan C, De S, Jung K, Muniyandi M, Hyun K, Srinivasan MA (2004) Haptics in minimally invasive surgical simulation and training. *IEEE Comput Graph Appl* 24:56–64
 62. Cosman PH, Cregan PC, Martin CJ, Cartmill JA (2002) Virtual reality simulators: current status in acquisition and assessment of surgical skills. *ANZ J Surg* 72:30–34
 63. Kim HK, Ratter DW, Srinivasan MA (2003) The Role of Simulation Fidelity in Laparoscopic Surgical Training, 6th International Medical Image Computing and Computer Assisted
 64. Chamarra MK, Dankelman J, van den Dobbelsteen JJ, Jansen FW (2008) Force feedback and basic laparoscopic skills. *Surg Endosc* 22:2140–2148
 65. Jacobs S, Holzhev D, Strauss G, Burgert O, Falk V (2007) The impact of haptic learning in telemanipulator-assisted surgery. *Surg Laparosc Endosc Percutan Tech* 17:402–406