Prevailing Trends in Haptic Feedback Simulation for Minimally Invasive Surgery

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Abstract

Background. The amount of direct hand-tool-tissue interaction and feedback in minimally invasive surgery varies from being attenuated in laparoscopy to being completely absent in robotic minimally invasive surgery. The role of haptic feedback during surgical skill acquisition and its emphasis in training have been a constant source of controversy. This review discusses the major developments in haptic simulation as they relate to surgical performance and the current research questions that remain unanswered. *Search Strategy*. An in-depth review of the literature was performed using PubMed. *Results*. A total of 198 abstracts were returned based on our search criteria. Three major areas of research were identified, including advancements in 1 of the 4 components of haptic systems, evaluating the effectiveness of haptic integration in simulators, and improvements to haptic feedback in robotic surgery. *Conclusions*. Force feedback is the best method for tissue identification in minimally invasive surgery and haptic feedback provides the greatest benefit to surgical novices in the early stages of their training. New technology has improved our ability to capture, playback and enhance to utility of haptic cues in simulated surgery. Future research should focus on deciphering how haptic training in surgical education can increase performance, safety, and improve training efficiency.

Keywords
minimally invasive surgery, haptic feedback, simulation

Introduction

According to Bholat et al,[1] haptics refers to the interaction between the tactile stimulus provided by one's environment, and a combination of cutaneous and kinesthetic sensors in tendons, joints and muscles. The perception of an object's stiffness, or contrarily, its compliance, requires a combination of visual and haptic components that varies depending on the amount and quality of information coming from either sense (e.g. sensory channel) and the ability to integrate this information with previous experience.[2] This suggests that despite the predominance of visual feedback while performing motor tasks, the addition of haptic feedback significantly accelerates the identification of objects and is vital to learning new motor tasks and improving coordination.[3]

Motor coordination is controlled principally by both visual and haptic feedback loops.[4] Zheng and MacKenzie[5] theorized that highly precise movements can overwhelm the bandwidth of the visual sensory channel, and that motor tasks that demand a high degree of accuracy are consequently more dependent on kinesthetic information provided by haptic feedback. They demonstrated that, when kinesthetic information is limited or attenuated by the introduction of a tool or instrument, performance deteriorates significantly when subjects are required to perform more accurate motor movements, such as those executed in surgery.

Surgeons have been able to counteract the detrimental effects of attenuated haptic feedback with extensive training and experience as well as by consciously and subconsciously placing more emphasis on visual cues. However, despite advances in imaging technology and high-definition video systems, visual compensation in minimally invasive surgery remains significantly different than that experienced in open surgery.[6] As a consequence, in inexperienced hands, these impediments result in prolonged procedural times and a greater risk for surgical error.[1,4] Furthermore, in situations where visual feedback is not as reliable, such as tele-operation, or with increased cognitive load, such as in 3-dimensional (3D) camera endoscopy, additional feedback provided by enhanced haptic feedback may be advantageous for improving recognition of critical structures such as blood vessels and gauging the appropriate force for tissue manipulation.[4,7-9]

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Cognizant of the attenuation of haptic feedback in minimally invasive surgery (MIS), surgical educators and scientists have designed MIS skills labs to maximize surgical realism by emphasizing haptic cues.[10] This is especially important, since haptic feedback has been found to be beneficial in the early phases of surgical skill acquisition.[11] Bench-top simulators are frequently utilized to create a training environment with similar or identical tissues and instruments, with the ultimate goal of replicating the haptic experience of the real-world operating room.[10,11] However, the parallel development of virtual simulation environments (virtual reality [VR] simulations) has been hindered by the inability to realistically replicate haptic feedback. This is primarily due to the technological challenge in rendering mechanical properties of instruments and tissues, in addition to a lack of understanding of how haptic feedback should best be delivered to the trainee.[4,12] This review provides an overview of the latest attempts to integrate haptic feedback into simulated surgery and its impact on surgical skills training. New advancements in this field, ongoing controversies and future problems are discussed since the last major review of this topic by van der Meijden and Schijven[4] in 2009.

Search Strategy

A literature search was conducted using PubMed to capture articles with the terms "haptic*" or "force feedback" or "touch feedback" and "minimally invasive surgical procedures" or "minimal invasive surgery" or "robotic surgical procedures" or "robotic" and "virtual reality" or "surgical training" or "surgical education". Reviews, randomized controlled trials and observational studies were included.

Our search strategy identified 198 abstracts relevant to haptic feedback and minimally invasive surgery. Manual review of each of the abstracts by the first author resulted in selection of 32 studies consistent with the focus of this review. Three major areas of investigation were consistently reported in the literature, including reports on the focused development of one of the four core components of a haptic feedback system, compensation mechanisms and utility of various tool and tissue interactions, as well as novel tools for enhancing haptic feedback in MIS and robotic minimally invasive surgery (RMIS) simulators.

Discussion

Components of Haptic Feedback Systems in Virtual Reality Surgical Simulators

Virtual reality–based surgical simulation was pioneered in the early 1990s by Delph and Rosen (1990) and by Lanier and Satava (1993).[13] Subsequently, many different models have been developed in a variety of surgical and clinical fields.[4] At the most elementary level, these VR systems consist of a processor unit that registers instrument movement and manipulation, which are then input into a software program that generates high-fidelity simulated environments for display on a monitor. A disadvantage of many of these systems is a lack of haptic feedback integration. However, newer and considerably more expensive technologies upward of US$ 30 000 have made this integration possible.[10,14] Basdogan et al[8] described 4 major areas of development for enhancing haptics in surgical simulation, including *interfaces*, *rendering*, *recording*, and *playback*. Each of these is explored below.

Haptic *interfaces* are devices through which the surgeon interacts directly with a variety of real or virtual environments. These are the tools that register movement and orientation in addition to applied forces with the use of the actuated joints that sample data between 300 and 500 Hz.[15] However, their availability is still restricted, limited by proprietary development and significant cost. This has resulted in a lack of benchmarks and interoperability with other systems. One possible solution that has been proposed is simplification of the haptic interface model (low fidelity) to decrease cost and facilitate interoperability.[15]

Haptic rendering in the VR environment represents the artificial or augmented sensation during organ-tool interactions that is constructed from 2 common tool-tissue interactions: long probes for palpation or blunt dissection and articulated tools for pulling and gripping.[8] The principal challenge of haptic rendering in surgical simulation is developing a realistic model for organ interaction in order to reproduce realistic tool-tissue interactions. Although visual constructs (3D computer rendered images) of various organs have been developed, the replication of interactions with these models is still unrealistic.[8] It has been proposed that skills transfer from VR simulation to the operating room could be improved by enhancing the simulated mechanical properties of the both the instruments and tissues.[16]

Haptic *recording* is the ability to record different surfaces, shapes and densities of the tissue based on the acquisition of these properties from 2 different methods: free-form human-controlled input using a sensor probe, and systematic scanning of these objects via a robot-controlled arm equipped with a haptic probe.[8] Currently, a considerable limitation in this area is that tissue samples have been restricted to cadavers and measured in a laboratory setting, making the measured physical properties (Young's modulus and Poisson's ratio) of these materials unrealistic. However, new research has been moving toward obtaining this information in vivo.[17] For instance, Beccani et al[18] developed a wireless palpation probe device for the intraoperative detection of soft tissue tumors. As the probe is manipulated by the surgeon with a grasper, the wireless palpation probe creates a volumetric stiffness map in real time to guide tissue resection with a sensitivity of 34 Pa and a maximum relative error of 5%.[18] Along the same lines, a piezoelectric sensor technology was developed by Omata et al,[19] which enabled a robotic hand to discriminate between objects at a level comparable to the human hand based on their hardness. Both of these technologies could foreseeably improve both the accuracy of haptic recording or provide a means of acquiring this information in real time.

Fortunately, the ability to convey simulated haptic information to the surgeon is improving. Haptic *playback* enables the trainee to follow prerecorded force and position trajectories.[8] Use of haptic playback may aid in the creation of training trajectories by way of closed loop motor control, which is motor control that requires continuous adjustment of muscle movements based on integration of perceptual cues.[10] For example, a haptic playback system could demonstrate to a novice the order in which fingers should move when tying a surgical knot.

A variety of both mechanical and electronic haptic compensation mechanisms, as well as augmentation devices, have been developed to compensate for the attenuated feedback experienced in laparoscopic surgery as a means to improve haptic *rendering*, the ultimate mechanical forces or tactile feedback provided to the operator.[8,15] From the mechanical perspective, graspers that reduce friction have been developed to reduce sensory loss typical of endoscopic tools. While these devices have not been able to completely restore haptic feedback, they have been able to measurably decrease sensory loss and enhance perceive feedback.[20] Examples of novel mechanical feedback mechanisms include a pneumatic array of 3-mm balloons developed for the da Vinci surgical system,[21] and the "SureTouch" device, which possesses 4 times more sensitivity than a human hand to detect breast tumors using 192 high-resolution pressure sensors.[22] The application of this technology to MIS might improve tissue identification, and would address one of the major limitations of robotic MIS (RMIS); nonetheless, it seems that vision may partially compensate for this haptic deficiency.

Compensation Mechanisms in Virtual Reality and Minimally Invasive Surgery Simulators

The concept of *visual haptics* in VR simulators was originally introduced by Lamata et al,[23] and further explored by Salkini et al[24] and Hagen et al.[25] The investigators found that in settings of attenuated haptic feedback, surgeons compensated with a "visual" sense of density and texture that develops with surgical experience. For example, experienced surgeons can anticipate when delicate maneuvers may be required for more friable tissue. This might explain why experienced surgeons retraining in RMIS may not necessarily demonstrate a significant performance deficit when haptic feedback is not available.[26]

Utility of Specific Components of Haptic Feedback

As described above, new technology continues to improve each of the four key components that comprise a haptic feedback system. At the same time, ongoing research has helped to identify which of these components provide the most benefit improving a surgeon's perception of the operative field. This portion of the review focuses on the surgeon's perception of and response to artificially generated or augmented haptic feedback.[9,12,27] The collective set of forces and torques perceived by the surgeon has been studied by Lamata et al[28] and are referred to as an individual's *perceptual boundar*y. Furthermore, the set of perceived forces deemed useful for carrying out a particular maneuver are known as the *utile boundary*.[28] Using this approach, Lamata et al[23] tested several surgeons' ability to perceive differences in tissue stiffness using laparoscopic tools and compared them with instrument based measurements of the same tissues. After obtaining the surgeon's subjective opinion of stiffness, the tissues were objectively tested in the laboratory and both stiffness scales were compared. The researchers found that when surgeons held large amounts of tissue in their grasper, the accuracy of their subjective assessment of stiffness increased. Additionally, the following 4 parameters were correlated with the ability to discriminate among different tissue types[23]:

a. Mass of tissue manipulated
b. Mass of tissue held with graspers
c. Tissue stiffness
d. Amount of fixation of the tissue to the abdominal wall.

These findings suggest potential areas for further development of simulators that incorporate haptic feedback. Given that a surgeon spends approximately 40% of operative time performing dissection tasks, a potential system should provide accurate and useful feedback regarding the total magnitude of the forces applied.[29] Wagner and his group[29] investigated haptic feedback during dissection tasks using a Personal Haptic Interface Mechanism (PHANToM) in a master-slave arrangement. They found that the use of force feedback decreased the amount of force applied as measured at the tip of an instrument, and reduced the overall number of errors.[29] The researchers suggested that the improved performance was a result of the simulated forces imitating natural physical constraints in the tissue.[29]

Similarly, the use of master-slave systems and amalgamations of laparoscopic tools with haptic interfaces provide alternate methods for enhancing haptic feedback in MIS. Tholey et al[30] integrated the PHANToM into a laparoscopic system to investigate the difference between using vision alone and vision combined with force feedback when learning laparoscopic surgical tasks. Their results demonstrated that force feedback improved the identification of tissues, resulting in superior dexterity, dissection, task time, and overall diagnostic proficiency during MIS.[30]

Current VR Simulators in General Surgery: Are They Effective?

At present, the most commonly used VR simulators in general surgery are the Minimally Invasive Surgery Trainer (MIST VR), Lap Mentor II, and LapSim.[10] Each system has its own merits, and will be compared here based on haptic feedback capabilities. The MIST VR (VP Medical R, London, UK) was the first virtual simulator developed and its ability to improve tool interaction and eye-hand coordination has been well established.[10] Its main purpose is to mimic basic surgical tasks with progressively increasing complexity, in addition to providing performance feedback and summative scores.[10] The lack of haptic capability in the MIST VR was intentional as it was originally designed as a task and instrument emulator rather than a realistic environment simulator. As a consequence, no effort was made to closely simulate the mechanical properties of different tissues. However, the absence of these advanced features has made the system more affordable and accessible.[10]

An additional simulator, the LapSim (Surgical Science Ltd, Gothenburg, Sweden) has a high face validity with more realistic tissue and tool interactions.[31] This system simulates several tasks, including instrument navigation, organ interaction, tissue damage measurement, camera steering and coordination, grasping, lifting, and cutting. In addition, it displays a variety of real-time feedback measures, including a performance score as a result of three areas measured: speed, efficiency, and precision.[31] This score consolidation is useful for construction of performance benchmark and allows mixing the different units of measurement of the areas evaluated. The LapSim haptic sensation is offered through the Xitact IHP haptic feedback instrument ports (Xitact, Morges, Switzerland) and handles. However, this haptic feedback has shown to offer increased frictional forces not inherent to laparoscopy, limiting the LapSim construct validity when employing haptic capabilities.[27]

Despite the aforementioned advantages, the benefit of haptic feedback in current VR systems remains controversial,[4,27,32,33] as demonstrated in a recent experiment by Brinkman and colleagues.[14] Brinkman et al[14] investigated whether the performance of a peg transfer task in a crossover study comparing a standard laparoscopic box trainer (lap box) with a Lap Mentor. The Lap Mentor (Simbionix USA Corp, Cleveland, OH) employs a software and microbot to create force feedback when interacting with tissues improving tactile feeling.[24] The investigators found that although performances in the box trainer and the VR simulator were correlated, participants who began training with the VR simulator required significantly more time to complete the task.[14]

While Brinkman et al[14] posited that the performance deficit might have been due to the addition of simulated haptic feedback, Yiasemidou and colleagues[34] found that its addition resulted in significantly faster performance of a laparoscopic cholecystectomy. Both studies comment on the nature of the tasks being performed and whether haptic feedback is useful in different surgical maneuvers such as grasping, pulling or dissecting. However, neither study addresses the maturity of the technology or whether the force feedback in this circumstance provides an appropriate surrogate for the natural haptic feedback a surgeon would encounter in the operating room or lap box.

Skill transfer from VR simulators that do not incorporate haptic feedback to the operating room has been validated previously,[4] yet there is still significant controversy regarding where haptics should be emphasized during surgical training to hasten skill acquisition.[32] This concept was investigated by Panait et al,[32] where 10 medical students (laparoscopic novices) executed a peg transfer and cutting task in the Laparoscopy VR (Immersion Medical, Gaithersburg, MD) both with and without haptic feedback. When force feedback was available, participants demonstrated improved performance in a cutting task, yet no statistical significance was found in the performance of a peg transfer task.[32] Similarly, Perrenot et al[35] validated the dV-Trainer (MIMIC Technologies, Seattle, WA), a virtual 3D haptic platform, as an assessment tool in robotic surgery. In this study, distance path and total time were significant criteria, with a high reliability scoring (r = 0.851), and 5 clearly differentiate levels of dexterity (P = .822).

Another important contribution is by Chmarra et al,[36] in which residents completed three separate laparoscopic tasks, each requiring different levels of force application in both a conventional box trainer and a VR trainer. The authors found that in tasks where force application was essential, trainees completing the task with nonattenuated haptic feedback performed better. This crossover study also demonstrated that those who trained with the VR model prior to completing a task using a box trainer did not perform as well, suggesting that haptic feedback only has a significant advantage when introduced early in the motor skill acquisition process.[36] Conversely, this effect may have been exacerbated by poor haptic rendering.

Additionally, Cao et al[37] explored the effect of haptic feedback on experience and cognitive load, which is the relative amount of mental attention required by a given task. In this experiment, the cognitive load was measured by comparing the performance of a primary task in addition to a less demanding secondary task. Participants were asked to perform mental arithmetic while completing a ‘TransferPlace’ task using the MIST VR (without haptic feedback) versus the ProMIS (with haptic feedback). Not only did the haptic feedback cohort improve performance (36% faster, 97% more precise) but these participants demonstrated reduced cognitive load.[37] One compelling finding was that the performance improvement was the greatest for experienced surgeons in the no cognitive load subgroup, implying that experts use spare cognitive capacity to focus on indirect haptic cues.[37] These results are congruent with those obtained by Botden et al,[38] in which 90 participants, 30 for each level of expertise (expert, intermediate, and novice), completed a suturing task and a basic skill task in both a ProMIS AR (Haptica, Dublin, Ireland) and the LapSim VR, where those aided by haptic feedback outperformed the haptic deficient cohort in all tasks.[38]

Recent Developments and Future Research Directions in Haptics

More recently, Zhou et al[39] studied the effect of haptic feedback on the learning curve of novices while performing laparoscopic suturing and knot-tying tasks in a haptic-equipped simulator, the ProMIS, or alternatively in the MIST-VR without feedback. The investigators found that complex tasks were learned more efficiently when haptic feedback was available during the early phases of surgical training. The participants were able to reach the first performance plateau more quickly and experienced the greatest benefit when learning suturing compared to knot-tying alone.[39] One limitation of this study is that posttraining evaluation was not completed; thus, the effects of haptics on skill retention and transfer to the operating room were not evaluated.[39] However, similar to previous investigations, this study again identified the early phases of surgical skill acquisition as the key point in time for emphasizing haptic cues.

Other contemporary studies have illustrated an improvement in precision and accuracy with force skill training in simulated environments,[9] as well as no negative effects on task time.[40] An example of this is the work developed by Chellali et al[41] with the Virtual Basic Laparoscopic Skill Trainer (VBLaST) (Rensselaer Polytechnic Institute, Troy, NY). In this study, the VBLaST and FLS trainer were compared in the peg transfer task in 30 subjects. Participants improved performance in the VBLaST compared with FLS (P = .05), but levels of expertise were not discernable. Since experts performed well only on the FLS trainer, authors surmised this phenomenon was possible due to the novelty of the technology.

Additionally, Trejos et al[42] developed a force-position metric of performance which demonstrated an ability to discriminate between 6 different levels of experience during a complex procedure consisting of 5 tasks. The procedure was composed of palpation, cutting, tissue-handling, suturing, and knot-tying tasks. The force-based metrics offer clear associations with experience than those with position-based metrics or task completion time ($P < .05$).[42] This study exemplifies an innovative method to use force-based metrics as an avenue for skill training and outcome measure for surgical procedures.

Factors Affecting Haptic Design in RMIS

Mimicking complete haptic feedback in robotics is difficult. Thus, current research is focused in the forces exerted during RMIS and sensory substitution.[26] Tavakoli et al[43] developed a robotic force/torque-sensitized end-effector (tool), specifically engineered for the possible future integration into a RMIS system. This end-effector measures tissue interactions and addresses the 3 design requirements in robotics of restricted size, proximal actuation, and tip sensor disposability. This device employs a noninvasive force interaction measurement using strain gauges, a linear motor, and a remotely actuated load cell. Being able to control force during RMIS with such type of devices may decrease the number of suture failures during procedures. New research in RMIS has elucidated an inverse relationship between suture failure frequency due to inappropriate force application and a surgeon's experience in robot-assisted dismembered pyeloplasty cases.[44]

In another recent study, Moradi Dalvand et al[45] found an improvement in correct tissue identification and appropriate palpation forces through force-enhanced haptic feedback in a Parallel Robot Assisted MIS System (PRAMISS) capable of measuring tool tip and tissue interaction forces with an actuated modular instrument with attenuation of forces if they were too high. This highlights the development of new RMIS technology that may improve or make safe tissue handling more consistent in the robotic setting.

Employing sensory substitution either by vibration or auditory to increase tool interaction awareness has been explored. Koehn and Kuchenbecker[26] developed 2 experiments executing dry-lab tasks in the da Vinci robot under 3 settings—both auditory and vibration feedback, only one of them, or none at all. In the first experiment, 10 surgeons and 10 nonsurgeons, 95% and 98% favored vibration feedback. The second experiment, 68 surgeons and 26 nonsurgeons, half were inclined to both types of feedback and the other half to just vibration feedback.

Conclusion

In the absence of reliable haptic cues, the main compensation mechanism utilized by MIS experts is visual-haptics. Even though novel investigations are incorporating haptic feedback in MIS, new research must be directed toward decoding the ways in which haptic training in surgical education may help make patients safer and decrease training times for new MIS techniques in the restricted work-hour era. This might involve deciphering the effect of haptic guidance on motor skill acquisition at a more detailed level as well as evaluate the effect of haptic feedback on skill retention mechanisms for skill transfer to the operating room. Parallel to these developments, future studies will need to focus on enhancing and standardizing tissue sensation through force feedback in RMIS.

Finally, the elucidation of haptic feedback on motor skill learning at different stages of skill acquisition will aid in the development of customized curricula where haptic feedback might be used to provide tailored guidance to each individual based on their level of training.

Author Contributions

D. Pinzon: Conception and design of work, writing of paper.
S. Byrns: Critical revision of paper.
B. Zheng: Critical revision of paper and final approval of version to be published. **[AQ1]**
Study concept and design: DP
Acquisition of data: DP
Analysis and interpretation: DP, SB, BZ
Study supervision: BZ

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