Laparoscopic surgery, perceptual limitations and force: A review

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ABSTRACT

Laparoscopic surgery (LS) has become the standard in procedures such as cholecystectomy and splenectomy. However, LS imposes limitations in visual and haptic perceptions, and create challenges unique to this type of surgery: reduced depth perception of the operative field caused by the use of 2D monitors; poor hand-eye coordination as a result of location of the monitor, variable amplification, mirrored movement, and misorientation; motion limitations due to trocar-induced invariant points, and reduced haptic feedback from the use of long and slender surgical instruments. One of the major concerns with laparoscopic surgery is potential for tissues damage, possibly caused by inappropriate use of force. Providing force feedback, either direct or augmented by visual/audio means, has the potential to improve laparoscopic surgical performance by reducing the peak force used during LS, and in turn reduce intra-operative injury to patients.

Keywords: laparoscopic surgery, haptic/force feedback, surgical performance

1. INTRODUCTION

Minimally invasive surgery (MIS) has become a common medical procedure. Laparoscopic surgery (LS) is a type of MIS performed by inserting Laparoscopic Instruments (LIs) through trocars via small incisions, usually into the abdominal cavity. Since the first laparoscopic cholecystectomy was performed in the United States in mid 1988[1], LS has become the standard for cholecystectomy[2], splenectomy[3], adrenalectomy[4], etc. The primary benefits of LS are reduced postoperative pain, shorter postoperative hospital stays, and faster recovery time for the patients[1, 5]. Although LS can be more cost-effective than traditional open surgery[6] (OS) in terms of reduced hospital stay, there is insignificant difference in *total* hospital cost between LS and OS[7]. Nevertheless, LS indirectly benefits society by allowing the patient to return to work more rapidly[6]. Yet LS has its limitations compared to OS. These limitations are of great interest to improvement of LS techniques and technologies. A more in-depth understanding of these limitations and the underlying factors will provide more direction for future research activities.

2. CHALLENGES IN LAPAROSCOPIC SURGERY

The setup of LS is very different from that of OS. In an open abdominal operation, for example, the surgeon simultaneously observes his/her hands, the instruments, and the operative field. In LS, an image of the operating environment is obtained by inserting an endoscopic camera into the body cavity, which is displayed on a video monitor. The surgeon views his/her operating environment indirectly and performs the surgical tasks bimanually using LI extended into the patients. Changes in the laparoscopic image views are controlled by an assistant. This particular setup, while beneficial to the patients, poses many limitations that increase the cognitive and physical load of the surgeons, and consequently the possibility for error, to the potential detriment of the patients. The challenges experienced by the laparoscopic surgeons and the underlying environmental and perceptual factors are elaborated upon in the remainder of this section.

2.1. Reduced Depth Perception

In OS, surgeons rely on direct visual input and are able to utilize various cues such as stereopsis to ascertain depth. In contrast, the monitors used in LS filter 3-dimensional cues from the operative field, resulting in a reduction of the depth cues available[8]. Depth perception is not entirely eliminated, however, as the monitor still provides monocular cues such as interposition or overlap, lighting, outline, texture, and motion parallax[8].

The effect of reduction in depth cues can be inferred from performance differences under different viewing conditions, as 3D video systems that restore stereoscopic vision are currently available. Unfortunately, contradictory evidence in the literature cannot confirm the advantage of a 3D system over 2D ones–some studies[9, 10] have shown that a 3D video system does not improve performance in terms of efficiency and quality of surgical techniques and execution time, while others[11, 12] show that 3D video systems enabled significant increase in speed and accuracy. Furthermore, experience and adaptation does not seem to be a factor influencing performance with difference video systems, as researchers cannot demonstrate any superiority of 3D system over 2D system between surgeons who have laparoscopic experience with those who have none[13]. As the experience of the surgeons, tasks performed, and equipments used in these studies were widely varied, more research is needed to determine the effect of depth cues on surgical performance.

2.2. Poor Hand-Eye Coordination

In addition to the reduction in depth perception, hand-eye coordination for laparoscopic surgeons is also impaired. The environmental factors that contribute to poorer hand-eye coordination are location of the monitor, variable amplification, mirrored movement, and misorientation[14].

The location of the monitor in LS impairs hand-eye coordination because the surgeon cannot see his/her hands and the operative field simultaneously. Experimentally, it has been found that surgical performance is significantly better when the monitor is positioned forward rather than to the left or right, and when the monitor is at the hand level rather than at the eye level[15]. Though some imaging systems such as the "Suspended Image System" and helmet-mounted displays (HMD) have been invented to simulate OS conditions by allowing simultaneous view of the operative field and surgeon hands, their effectiveness has yet to be confirmed in the field of LS as these technologies are still being enhanced.

Variable amplification and mirrored movement are the result of the rotation of instrument shafts around the incision points[14]. Movement perpendicular to the instrument shaft is amplified or reduced depending on the location of the incision point along the shaft. The endoscopic camera and the monitor further magnify this variable amplification, creating a discrepancy between the magnitude of the movement interpreted by the body's kinesthetic feedback and that presented on the monitor. Also, handgrip movements perpendicular to the instrument shaft are mirrored at the incision point, again resulting in discrepancy between actual surgeon’s movement and what is shown on the monitor. Fortunately, experiments in the literature show that surgeons can adapt to these scaling and mirror effects[16,17].

A more serious problem is the effect of misorientation caused by a mismatch between the line-of-sight of the surgeon and that of the camera controlled by an assistant, because this particular disturbance is larger and cannot be easily overcome. This spatial misorientation can be further resolved into three planar misorientations: one parallel to the monitor and two perpendicular to the screen[14]. Experiments by numerous researchers show that misorientations lead to significant decrease in performance[18-21], and that with a 90° reorientation of the endoscopic camera such that the misorientations between the movements of the displayed instrument and the actual instrument were eliminated, significantly faster task completion time as well as lower mental load can be achieved[22]. However, this method of reorientation also rotates the position of the internal organs, resulting in potential confusion[14]. Technical solutions for the compensation of planar misorientation are still in the process of being enhanced and validated. As such, planar misorientation results in increased navigational difficulties for laparoscopic surgeons.

2.3. Motion Limitation

In LS, the trocar restricts movement by acting as invariant points[23]. The range of motion is therefore reduced to four degrees of freedom compared to six needed to perform free motion, negatively affecting the surgeon's dexterity[16]. Precise effect of this restriction in motion on surgical performance is yet unknown, but preliminary work gives insight into possible consequences – for instance, it was found that more motions are made using a LI by both students and expert surgeons during training workshops compared to an ideal, unconstrained performance[24]. Furthermore, not all of the motions using LIs are wasteful; some of the motions are used for information-gathering purposes, suggesting possible strategy differences between open and laparoscopic surgeries.

Ergonomic analysis of LS tasks reveals that there are significant ergonomic problems with the use of LIs, which result in more discomfort for the surgeons. One survey showed that the use of a LI caused more upper extremity discomfort in laparoscopic surgeons[25]. Another study led to the conclusion that LS requires greater concentration and places greater mental stress on surgeons[26]. Although poor mechanical efficiency and configuration of LIs were listed as possible causes of poor ergonomics in laparoscopic tasks[25], causation of physical discomfort was not established. It is possible that the setup in LS restricts motion, promotes a different movement strategy, and consequently leads to increased physical discomfort.

2.4. Haptic Feedback

Haptic[*] feedback is reduced in LS due to the use of long and slender LIs. The role of haptic feedback is of special interest because it is used in important decision-making scenarios such as the discrimination of healthy versus abnormal tissues, identification of organs, and motor control.

Although surgeons cannot directly touch the internal organs and tissues, haptic feedback is present during LS. Bholat et al[27] have shown that surgeons are able to determine shape, texture, and consistency in the absence of visual feedback using direct palpation (DP), conventional instrument (CI), and LI. Not surprisingly, shape or object identification using a LI is inferior to a CI and DP. However, no statistically significant improvement is observed between DP, a CI, and a LI in consistency determination. Furthermore, texture discrimination is better with LI. The ability to perceive roughness using a LI is again affirmed by s study which showed that inexperienced laparoscopic users were able to perceive surface roughness using LI with and without visual feedback[28].

2.5. Implications

The investigation of challenges in LS and underlying perceptual factors emphasizes limitations in visual and haptic perceptions as two complex and interconnecting issues involved in LS. Under normal circumstances, the redundancy in the human perceptual modalities enables us to compensate for inadequacies in one modality with cues from other modalities. For instance, it has been shown that audio and visual cues are involved in the perception of surface roughness as well as tactile cues[28,29]. However, in the case of LS, both visual and haptic perceptions are impaired, resulting in a less accurate estimation in general when visual and haptic cues are integrated.

It is clear from the perceptual limitations and their consequences that LS requires a different motor and perceptual skill-set compared to OS, and training and significant experience are needed to attain competency[30, 31]. Of the research areas pertaining to LS, force feedback deserves special attention because it is affected by both visual and haptic perception, as well as cross-modal interaction of the two perceptual streams. Manifestations of force in current laparoscopic problems reveal interesting insight into the role of force feedback and human perception/performance.

3. FORCE AND LAPAROSCOPIC PERFORMANCE

So far, only some of the problems faced by surgeons have been discussed. These problems are caused by inherent limitations in visual and haptic perceptions imposed by LS, which increase cognitive and physical stress of the surgeons and lead to less accurate judgement and estimation. It is not surprising that laparoscopic procedures take significantly more time to perform compared to their OS counterparts [7, 32].

A major concern with LS is increased intra-operative injury: trauma caused at the instrument-tissue interface. One national survey found that the laparoscopic cholecystectomy procedure is associated with a significant rate of bile duct injury–recognized postoperatively in half of the cases and most frequently required anastomotic repair[33]. A later population study showed that the proportion of all cholecystectomy cases with intra-operative injury increased from 0.67% in 1988-90 to 1.33% in 1993-94 after the introduction of the laparoscopic cholecystectomy procedure[34]. The study went on to establish that compared with open cholecystectomy, laparoscopic cholecystectomy carries a nearly twofold higher risk of major bile, vascular, and bowel complications. What might be the cause of this?

The answer could be the inappropriate use of force. In a modified human reliability assessment study, 20 laparoscopic cholecystectomy procedures were recorded and analyzed for error[35]. The most serious consequence of any of the

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[*] The term *haptic* feedback is used here, even though the terms *haptic* and *tactile* feedback appear interchangeable in literature – for example, Bholat et al.[27] referred to the ability to discriminate shape, texture, and consistency as tactile feedback. According to Loomis and Lederman[44], tactile and kinesthetic perception are mediated solely by variations in cutaneous and kinesthetic stimulation respectively, while haptic perception is defined as tactual perception in which both the cutaneous sense and kinesthesis convey significant information. In LS, the perception essential in the determination of properties such as shape, texture, and compliance is haptic in nature, as it requires both cutaneous and kinesthetic feedback.

observed errors was the perforation of the gallbladder, which occurred in *15* of the 20 total procedures. The role of force became more apparent upon closer examination of the data–of the 15 procedures that resulted in gallbladder perforation, 11 of which cited "too much force/rotation/displacement" as one of the errors committed. It was suggested that one of the possible causes for the observed results is that an inappropriate level of force is applied due to diminished tactile and force feedback[35].

The role of force is again highlighted in a study of errors[36] enacted by surgical trainees during simulated laparoscopic cholecystectomy on restructured animal tissue. Analysis of 60 video-taped simulated laparoscopic cholecystectomy procedures by the trainees revealed a total of 331 consequential errors, 183 of which resulted in intra-operative injury. All intra-operative injuries had "use of excessive force with instrument" as one of the errors contributing to the injuries. In summary, 55% of the consequential errors were due to "a step being done with too much force/distance". In contrast, inconsequential errors had 9% of too much force/distance, but 21% of too *little* force/distance. The authors pointed out that difficulty in gauging the right force to avoid intra-operative injury is further compounded by diminished tactile feedback and especially by the friction between the shaft of the LI and its incision point.

Providing feedback is one way of amending the problem of inappropriate force usage. The improved accuracy in roughness estimation when both visual and haptic cues are available has already been demonstrated[29, 28]. In a recent study, researchers developed an automated laparoscopic grasper with force feedback capabilities, and tested the ability of surgeons as well as non-surgeons in characterizing tissue softness under visual feedback only, force feedback only, and visual plus force feedback conditions[37]. This study confirmed the hypothesis that providing both vision and force feedback leads to better tissue characterization than having vision feedback only or force feedback only. Having force feedback has also been shown to reduce the maximum force exerted by approximately 40%[38]. Conversely, absence of force feedback lead to a significant increase in average and peak forces used[39]. Yet another study showed that force feedback need not be provided using force, but substituted by visual feedback, and that visual force feedback can reduce the peak and average contact forces compared to force feedback only [40].

Neither of the error analysis studies provided a detailed analysis of misorientation and of rotation/displacement and that of distance[35, 36]. Therefore, it is not known if overshooting of distance is a result of variable amplification and mirrored movement effects. However, it is easy to infer from previous findings that the visual and haptic perceptual limitations would result in poor navigation in LS, in turn contributing to the longer operation time required to perform laparoscopic procedures. Visuo-spatial navigation is an essential part of any surgery, so how does it affect the use of force? Could the surgeons and trainees be using excessive force in order to gather more navigational cues? These are valid questions to ask, because in the exploration of the operative environment, there would be a lot of curvilinear movement traced by the LI. How the estimation of distance/location is affected in this instance is yet unknown. However, it has been demonstrated that with no visual feedback, judgements of kinesthetic distance between two points in space or between the fingers of two hands are subject to considerable over-estimation error[42]. Do similar results hold for haptic exploration and distance estimation using LIs? If so, then the consistent over-estimation of distance could possible explain the overshooting of displacement and force, as surgeons would be exerting forces for targets located further away in their mental model, only to encounter the intended objects much sooner due to distance misjudgment.

Questions concerning haptic exploration and distance estimation raise the issue of how haptic cues are used. In a different experiment[42], researchers found that in a spatial task, kinesthetic target location information shows no appreciable decay after 10 seconds, while visual location information shows rapid memory decay in the same time period. However, we do not know how laparoscopic surgeons rely on haptic versus visual cues, and there could be great variation from individual to individual. Further research into haptic encoding[43] of object location, and the interaction between navigation and use of force could contribute to the understanding of cognitive and kinesthetic processes involved in LS.

4. CONCLUSION

The literature research presented in this paper has highlighted several challenges associated with LS, namely, reduced depth cues, poor hand-eye coordination, motion limitation, and diminished haptic feedback, all of which contribute to increased perceptual and cognitive load of laparoscopic surgeons. The environmental and perceptual factors behind the challenges arise from the particular setup of LS, such as the use of 2D video system to provide indirect view of the operative field, the small incisions as access points for the surgeons, and the use of long and slender LIs in surgery. It is anticipated that the exploration of these environmental and perceptual factors will help with a broader understanding of LS and provide insights into potential research topics.

One such potential research topic is the role of force in laparoscopic surgical performance. The use of force, force feedback, and interaction with other tasks in LS procedures such as compliance discrimination and the navigation of operative field embody a gap in the research areas connected to LS. In depth investigation of how force in LS is affected by other factors and how humans encode haptic cues in visuo-spatial navigation involves cross-disciplinary research in psychology, kinesiology, ergonomics, etc.

Force related research provides an opportunity to quantify surgical experience, because it is objectively measurable. Findings in the role of force in laparoscopic procedure will be applicable to not only LS, but robotic surgery, tele-surgery, virtual reality simulation and modeling of laparoscopic procedures, and virtual training of laparoscopists. Ultimately, the goal of force-related research is to reduce the cognitive and physical stress experienced by laparoscopic surgeons, thereby benefiting patients in terms of increase in safety, efficacy, and cost-effectiveness.

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