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Three-dimensional vision enhances task performance independently of the surgical method

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Abstract
Background Within the next few years, the medical industry will launch increasingly affordable three-dimensional (3D) vision systems for the operating room (OR). This study aimed to evaluate the effect of two-dimensional (2D) and 3D visualization on surgical skills and task performance.
Methods In this study, 34 individuals with varying laparoscopic experience (18 inexperienced individuals) performed three tasks to test spatial relationships, grasping and positioning, dexterity, precision, and hand–eye and hand–hand coordination. Each task was performed in 3D using binocular vision for open performance, the Viking 3Di Vision System for laparoscopic performance, and the DaVinci robotic system. The same tasks were repeated in 2D using an eye patch for monocular vision, conventional laparoscopy, and the DaVinci robotic system.
Results Loss of 3D vision significantly increased the perceived difficulty of a task and the time required to perform it, independently of the approach ($P < 0.0001$–0.02). Simple tasks took 25 % to 30 % longer to complete and more complex tasks took 75 % longer with 2D than with 3D vision. Only the difficult task was performed faster with the robot than with laparoscopy ($P = 0.005$). In every case, 3D robotic performance was superior to conventional laparoscopy (2D) ($P < 0.001$–0.015).
Conclusions The more complex the task, the more 3D vision accelerates task completion compared with 2D vision. The gain in task performance is independent of the surgical method.

Keywords 2D · 3D laparoscopy · 3D vision · Robotic surgery · Surgical skills · Task performance

In recent years, minimally invasive surgery has demonstrated benefits for easy to moderately complex surgical interventions compared with conventional open surgery [1–5]. These advantages and the continuous gain in experience have resulted in a willingness to perform more complex laparoscopic procedures [1, 6, 7]. Still, advanced laparoscopy is extremely challenging due to technical limitations [8], with the result that surgeons must undergo extensive training and experience flat learning curves to provide patients with safe, minimal access surgery. To allow for safe laparoscopy in more complex surgical areas and to ease potential novel endoscopic techniques (e.g., natural orifice transluminal endoscopic surgery [NOTES]), technical innovations in the field must keep up with surgeons' demands.

Besides general shortcomings, such as the fulcrum effect or decreased haptic feedback, and despite the technical

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limitations of instrument design, two-dimensional (2D) vision on a flat screen has been identified as a major disadvantage of laparoscopy compared with open surgery [9–11]. Major advances in the development of surgical video imaging has mainly concerned image quality, leading to bright, high-resolution images. However, improvement in depth perception by three-dimensional (3D) vision has been hampered by technical and financial limitations.

Experienced surgeons can compensate for the lack of the third dimension by using indirect clues such as the movement of the endoscope/motion parallax perspective, relative size, shading, texture gradient, familiar anatomy, and the size of anatomic structures [12, 13]. With the advances in 3D technology evident in the increasingly popular 3D movies and surging 3D products in the home entertainment segment, the medical technology industry expects the emergence of affordable and high-quality 3D vision systems in the operating room on a large scale in the next 2–3 years (in analogy to high-definition [HD] products).

Several researchers have compared the role of 3D imaging with the traditional 2D mode during laparoscopy [14–29] and robotic surgery [30–38]. The advantages of 3D over 2D vision are consistent in robotic surgery, but the results for conventional laparoscopy differ greatly. Some studies have indicated equivalent task performance, whereas others have detected superior outcomes for some or all tasks performed using 3D vision. These differences appear to originate mainly from incoherent study designs and the use of inferior, earlier-generation 3D vision systems that provide video quality with low image resolution and only near real-time transmission. Thus, no definite conclusion can be drawn from the literature, especially for laparoscopy.

This study aimed to assess the overall role of 3D vision during surgical performance in open, laparoscopic, and robotic tasks. The use of an up-to-date 3D laparoscopic vision system allowed for a direct comparison with high-resolution monitors.

Materials and methods

Participants and tasks

The difference between 3D and 2D vision was evaluated in 34 individuals with varying surgical experience. Only subjects with normal or corrected-to-normal vision were selected. The mean age of the 34 participants (20 men and 14 women) was 31.8 years (range, 23–47 years). The majority of the participants ($n = 19$) had fewer than 3 years of professional surgical experience, whereas 16 participants were already experienced laparoscopic surgeons. The inexperienced surgeons were either interns (last-year medical students) or first- and second- year surgical residents with an experience level of 20 or fewer basic minimally invasive procedures. The experienced surgeons were board-certified attending surgeons with a minimum of 100 minimally invasive surgical procedures.

Each individual performed three tasks (T1–T3) using open, laparoscopic, and robotic surgical techniques (Fig. 1). All the tasks were performed in 3D first, followed by the same tasks in 2D to exclude bias due to the learning effect. Each participant was instructed concerning the specific tasks to be performed. The participants were allowed to practice each task two times before registering the performance. All the participants performed the tasks in an identical sequence under identical conditions.

Three different skill pods ((The Chamberlain Group, Great Barrington, MA, USA) used for introducing practitioners to the skills required for minimally invasive surgery were used for the tasks (Fig. 1). Task 1 (T1) tested 3D imaging and spatial relationships. To test simple grasping and positioning maneuvers, we used the Sea Spike Pod containing soft cones of different sizes and shapes. Three small rubber rings were placed over one soft cone. The participants were required to grasp and distribute the rings one after another, placing them over three separate predetermined cones. Subsequently, the rings had to be transferred back to the initial cone.

Task 2 (T2) tested dexterity by suturing (without knot-tying) of a simulated gaping skin incision (Skin Suturing Pod). In this drill, three continuous stitches were placed in parallel.

Task 3 (T3) tested dexterity and precision using a suture with a curved needle (Vicryl 3-0; SH, Ethicon Inc., Cincinnati, OH, USA) that had to be passed from hand to hand through 10 small flexible eyelets. The eyelets were numbered and arranged in a S-curve and had to be passed in numeric order (S Hook Pod).

Each task required an appropriate amount of two-handed coordination and ambidexterity, which are considered essential for testing depth perception. Each task was evaluated by the time needed to complete the task. After the completion of each module (open, laparoscopic, robotic), the participants were asked to estimate the difficulty of the task on a visual analog scale (VAS) ranging from 1 (very easy) to 10 (extremely difficult to barely realizable).

Imaging systems

Each task was performed in both 3D and 2D vision (Fig. 1). Binocular vision was used to express true 3D vision for open performance, whereas monocular vision was achieved by covering one eye with an eye pad. Monocular vision should at least partly mimic a 2D

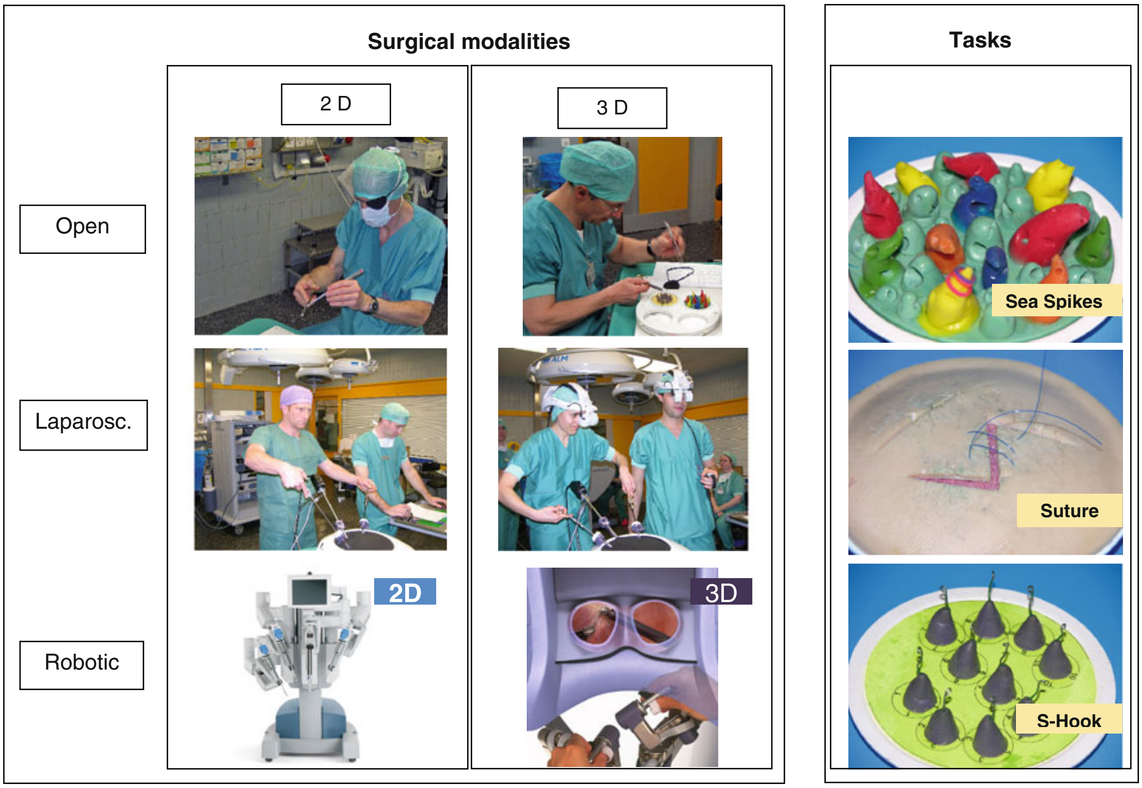

Fig. 1 *Left* The surgical modalities (open, laparoscopic, robotic) and the way that two-dimensional (2D) and 3D vision was implemented. The robotic DaVinci system allowed for direct switching between the 2D and 3D modes. *Right* The tasks to be performed are shown. Task 1: Sea Spike Pod for 3D imaging and spatial relationship testing. Task 2: Suture Pod for testing dexterity by suturing of a simulated gaping skin incision (without knot-tying). Task 3: S-Hook Pod for testing dexterity, precision, and manipulation with both hands (needle transfer)

environment by taking away binocular disparity, an important visual cue that estimates distance and provides information to the brain, in which depth perception is extracted from the two 2D retinal images.

The EndoSite 3Di Digital Vision System (Viking Systems, La Jolla, CA, USA) was used for 3D laparoscopic performance. This system couples a 3D view with a head-mounted display, allowing spectral depth perception with the use of traditional laparoscopic instrumentation. The system includes a stereo digital scope (dual three-chip charge-coupled device [3CCD] optical channel) attached to a 3D data-processing unit, which conveys information to a head-mounted display. The head-mounted display consists of three liquid crystal displays (LCD) per eye (HD-SDI, 1080i monitor) attached to a headset, allowing for stereoscopic 3D vision.

The 2D laparoscopic system (Karl Storz, Tuttlingen, Germany) consisted of a standard laparoscopic video tower with a 10-mm, 30° scope and a 3CCD digital system attached to a 23-in. HD (1080i) flat screen video monitor. The optics were optimized in both systems before the performance of the task, and lighting was adjusted to similar levels for all systems. The laparoscope was adjusted and remained fixated during task performance. In all tasks, the participants used the same laparoscopic instrumentation to complete the task.

The DaVinci S Surgical System (Intuitive Surgical Inc., Sunnyvale, CA, USA) was used for robotic surgical performance in the 3D or 2D mode. The InSite 3D endoscope (EndoSite 3Di Digital Vision System, Viking Sys-tems, La Jolla, CA, USA) provided two separate vision channels linked to two separate color monitors. The images were presented directly in the viewer on two continuous-tone cathode-ray tube monitors to produce a clear 3D image. The right and left eyes received separate images from each camera to a set focal point. Two 3CCD cameras with 800 lines of resolution were used. This vision system also incorporates the Intuitive Surgical image processing equipment, which is composed of high-performance video cameras and specialized edge enhancement and noise reduction equipment.

Statistical analysis

Student's *t*-test was used to test for differences between two groups, and one-way analysis of variance (ANOVA) was used to compare several groups. The Wilcoxon signed-rank test was used for repeated measures. A *P* value less than 0.05 was considered significant. Calculations were performed using NCSS 2001 (Number Cruncher Statistical Software, Kaysville UT, USA).

Results

Task performance in 2D was considered more difficult than in 3D

The 34 participants were questioned about the subjective difficulty of the performed tasks. The tasks were rated immediately after completion of each task with each modality. The Sea Spike task was perceived as the easiest, whereas the S Hook task was rated as difficult (in 3D) to very difficult (in 2D). For all the tasks in all surgical modalities, the perceived difference in difficulty was significantly higher in 2D than in 3D (Table 1). The difference between 2D and 3D was independent of the laparoscopic experience. Generally, the open technique was considered the easiest way to complete a task. The laparoscopic modality was perceived as the most difficult way to solve a task, with robotic surgery having a slight advantage for experienced laparoscopic surgeons.

3D vision allowed faster task performance than 2D vision

We used the task completion time for objective determination of task difficulty and individual participant performance. The open modality allowed for the fastest task completion, and 3D vision allowed for faster completion than 2D vision. The difference between 3D and 2D vision remained significant over all the tasks, independently of the surgical modality chosen ($Pmax = 0.02$, Wilcoxon signed rank test; Fig. 2).

All task performances started in 3D vision mode to eliminate improved performance due to the effect of training and learning. The time required to complete a task corresponded well with the perceived task difficulty.

The increased time to perform a task in 2D depended on task difficulty, not method

Two-dimensional vision reduced the speed at which tasks were completed by 19 % to 88 % (3D time was used as a reference, 100 %; Table 2). The performance time due to the loss of 3D vision increased 19 % to 31 % for the suture task, in which haptic feedback is a relevant factor (a stitch also can be performed blindfolded).

Time loss was more homogeneous than the other tasks, which depended predominantly on vision. The Sea Spike task, perceived as an easy task, took approximately one-third longer when vision was reduced to 2D. The difference between 3D and 2D vision became more pronounced when the difficult S Hook Pod task was completed and led on the average to a 75 % (range, 69–88 %) time increase when 3D vision was lost. Interestingly, the additional time required to perform a task in 2D compared with 3D depended on the difficulty of the task itself and, to a much less extent, if at all, on the surgical method.

Table 1 Rating of task difficulty depending on experience and vision[a]

Rating of tasks (VAS)	Sea spikes		Suture		S Hooks	
	2D VAS	3D	2D VAS	3D	2D VAS	3D
Open						
No exp	2.8 ± 1.2	1.4 ± 0.7	3 ± 1.0	1.7 ± 0.7	4.1 ± 1.5	2.5 ± 1.1
Lap exp	2.8 ± 1.0	1.3 ± 0.7	2.1 ± 1.1	1.1 ± 0.3	4.7 ± 1.6	2.6 ± 1.3
2D vs 3D	$P < 0.001$		$P < 0.001$		$P < 0.001$	
Laparoscopic						
No exp	5 ± 1.4	3.9 ± 1.1	6.6 ± 1.4	5.9 ± 1.9	8.5 ± 1.3	6.7 ± 1.8
Lap exp	4.2 ± 1.8	2.9 ± 1.2	4.9 ± 1.6	3.7 ± 1.2	7.7 ± 1.5	5.7 ± 1.6
2D vs 3D	$P < 0.001$		$P = 0.005$		$P < 0.001$	
Robotic						
No exp	3 ± 1.3	2.28 ± 1.4	5.5 ± 2.2	4.7 ± 2.3	6.7 ± 1.2	5.2 ± 1.7
Lap exp	3.9 ± 1.8	2.67 ± 1.7	4.6 ± 1.7	3.3 ± 1.5	6.5 ± 1.3	4.4 ± 1.6
2D vs 3D	$P < 0.002$		$P = 0.005$		$P < 0.001$	

2D two-dimensional, *3D* three-dimensional, *VAS* visual analog scale, *No exp* participant with no or minimal laparoscopic experience, *Lap exp* experienced laparoscopic surgeon

[a] P values are calculated for the difference in means between 2D and 3D ($n = 34$; t-test)

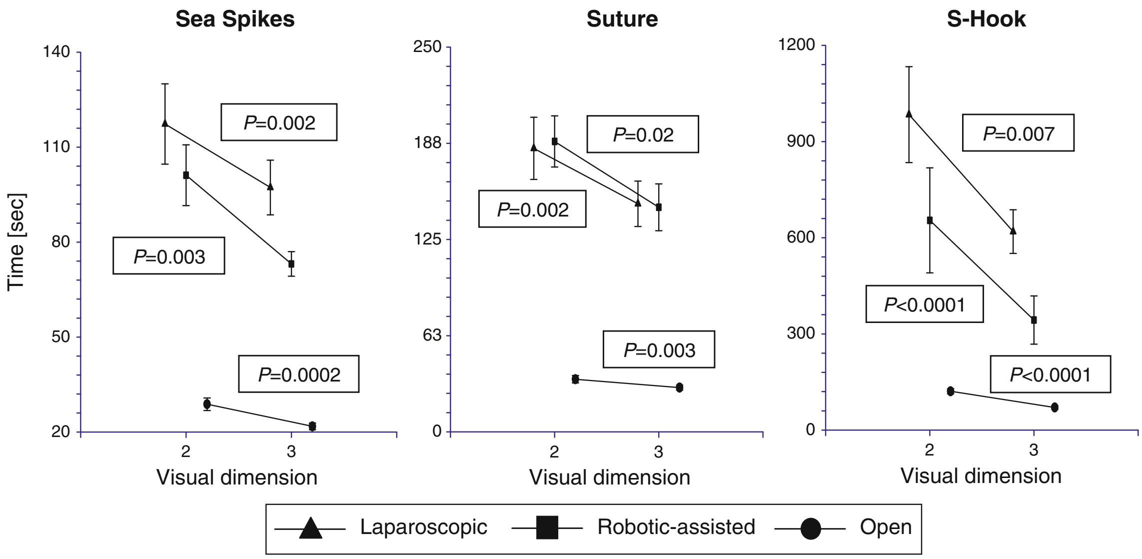

Fig. 2 Task completion is faster with three-dimensional (3D) vision than with 2D vision. The median time used to complete the three tasks for each of the surgical modalities is shown. The difference between the 2D and 3D times were calculated for each participant individually. Thus, the 2D and 3D medians are connected for better visualization of the paired data. Error bars represent the standard deviation. All tasks were completed faster with the open modality. The *P* values were calculated by the Wilcoxon signed-rank test for repeated measurements

Table 2 Difference in percentage of time required to complete a task in 2D compared with 3D

Surgical modality	Sea spikes (%)	Suture (%)	S Hook pad (%)
Overall	33	25	75
Open	32	19	69
Laparoscopic	30	28	71
Robotic	38	31	88

2D two-dimensional, *3D* three-dimensional

Robot-assisted task performance tends to be faster, independently of vision

For all tasks, the open surgical method remained significantly faster than the laparoscopic or robotic technique. The difference between laparoscopy and robotic surgery mainly consists of a reduced but preserved haptic feedback for laparoscopic instruments, with the DaVinci robot allowing for a greater range of motion.

We eliminated the influence of depth perception by comparing performance in 2D and 3D. Only in the suture task, which requires haptic feedback to some extent, was laparoscopic performance comparable with the robotic performance (3D vision: mean laparoscopic time, 155.6 s; 95 % confidence interval [CI] 121.3–190 s vs mean robotic time, 142.3 s; 95 % CI, 107.5–177.1 s; $P > 0.05$; Fig. 3). For tasks less influenced by haptic feedback, task completion in 3D was significantly faster with the robot than with laparoscopy (Sea Spike: laparoscopic mean time, 99.6 s; 95 % CI, 78.1–121 s vs robotic mean time, 69.5 s; 95 % CI, 63.1–76 s; $P = 0.004$; Fig. 3). For the more demanding S Hook task, the according means were 600 s (95 % CI, 429–770 s) for laparoscopic performance and 343 s (95 % CI, 186–500 s) for robotic performance ($P = 0.005$, Wilcoxon signed rank). Interestingly, the difference between the two methods was more pronounced in all tasks with 3D vision.

Robotic performance in 3D is superior to conventional laparoscopy in 2D

Subsequently, we addressed the difference in depth perception between conventional laparoscopy (typically 2D mode) and robotic surgery with the DaVinci system in 3D. All the tasks were performed significantly faster with the 3D robotic modality than with 2D laparoscopy. The mean time for the Sea Spike task was 121.8 s (95 % CI, 93.3–150.3 s) with laparoscopy and 70.8 s (95 % CI, 64.1–77.4 s) with robotic surgery ($P < 0.0001$). The mean times were 191.7 s (95 % CI, 149.1–234.3 s) versus 142.1 s (95 % CI, 110.3–173.7 s); $P = 0.015$, (Wilcoxon signed-rank test) for the suture task and 824.8 s (95 % CI, 510.3–1139.4 s) versus 343.3 s (95 % CI, 186.5–500.1 s); $P = 0.0003$, (Wilcoxon signed-rank test) for the S Hook task. These findings put previous reports about the comparison of laparoscopic and robotic skills into perspective because the skills were compared under different visual conditions, namely, under 2D versus 3D vision.

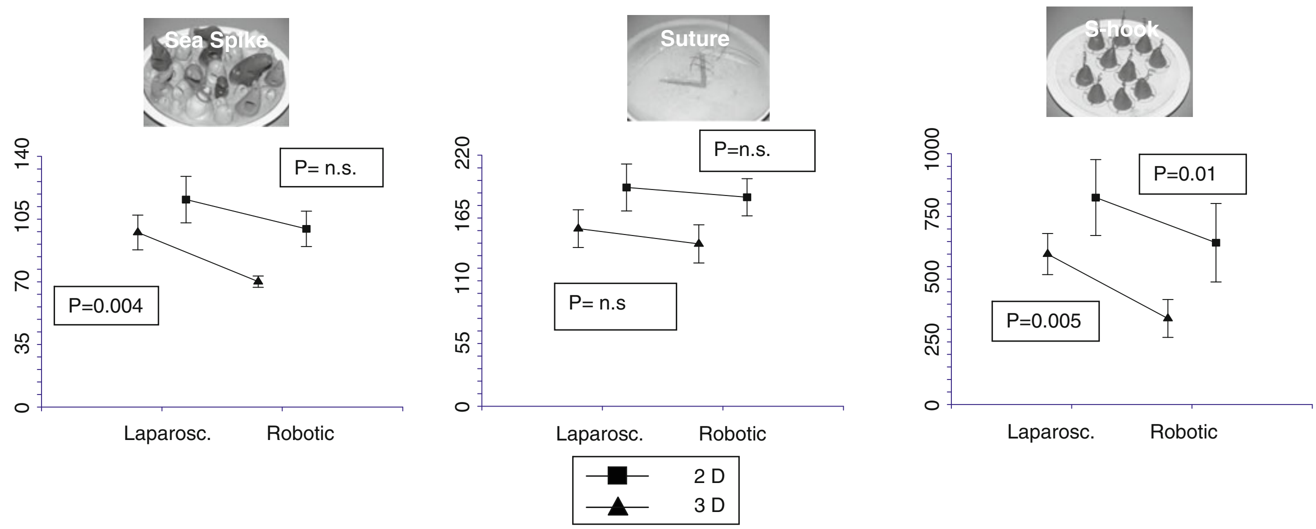

Fig. 3 A trend toward faster task completion with the robotic modality than with the laparoscopic modality was observed. The median times for task completion with the laparoscopic and robot-assisted modalities are shown (both two-dimensional [2D] and 3D vision are shown). The medians are connected to emphasize the paired analysis of each participant's performance in the two modalities. Error bars represent the standard deviation. For the suture task, haptic feedback was considered helpful for completion of the task. The difficult S Hook task took considerably more time with laparoscopic surgery than with robot-assisted surgery (*P* values were calculated using the Wilcoxon signed-rank test)

Discussion

The data presented show that task performance with 3D visualization is superior to that with 2D visualization independently of participants' laparoscopic experience, the difficulty of the task, or the surgical modality.

Although 3D visualization is intuitively considered an important and contributing factor for improved performance during minimally invasive surgery, publications comparing 2D and 3D vision in the last two decades have reported contradictory results [14–24, 33, 39, 40].

When laparoscopic skills are assessed, two major requirements seem to be paramount: ability to translate information received from a 2D image to the 3D visceral organ situs (visiospatial translation and perception) and psychomotor hand–eye coordination [41]. To reach an expert level, the acquisition of both skills demands sustained and deliberate practice over years. Thus, learning curves for complex and advanced conventional laparoscopy are flat and slower compared with those for open surgery, requiring extensive training and experience [42].

Our findings corroborate previous studies describing the advantage of using the 3D mode over the 2D mode during robotic surgery and the superiority of advanced 3D optical systems over conventional 2D laparoscopy. Conflicting findings in several other studies are most likely the result of using less efficient 3D vision systems. The technical quality of 3D vision systems appears to have a drastic effect on overall task performance. It is not surprising that a significant difference between 2D and 3D vision was observed in our studies because we used modern high-definition 3D systems that had already been tested in clinical practice. Not only was task completion time accelerated, but the tasks were perceived as significantly easier with 3D vision than with 2D vision.

Another interesting aspect of this study was the assessment of robot-assisted performance versus laparoscopy independently of the difference in visual dimensions. Conventional laparoscopy relies on 2D vision, whereas robotic surgery, using the only commercially available Food and Drug Administration (FDA)-approved robotic system, is performed in 3D vision.

A direct comparison of laparoscopy with robotic surgery found that the robotic surgical system allows steepening of the learning curve for almost any laparoscopic procedure [34, 37]. This improvement was attributed to superior ergonomics and enhanced dexterity, precision, and control, as well as to improved 3D visualization. However, we did not investigate the extent to which the additional depth perception accounted for the better performance.

Our results showed little to no difference between robot-assisted and laparoscopic performance for easy tasks, especially if a certain degree of haptic feedback is helpful for task completion. For difficult tasks, 3D vision and robotic assistance resulted in a faster performance compared with laparoscopy. Given that 3D robotic performance was significantly superior to 2D laparoscopic performance, the most important difference in task performance between conventional laparoscopy and robot-assisted surgery is vision. This is especially true when spatial limitations are absent. This importance for 3D vision has been suggested repeatedly by other researchers [12, 32, 35, 37].

Arguably, the most interesting finding of this study was that 3D vision improved the task completion speed according to the difficulty of the task. The modality in which the task was performed played no major role. In other words, regardless of the surgical approach chosen, the loss of 3D vision delayed the completion of a task proportionally to the difficulty of the task. This finding should translate directly into clinical practice. For more demanding procedures, the gain in operating time would favor the use of a vision system with depth perception independently of the surgeon's experience. An efficient 3D optical system would facilitate advanced laparoscopic surgery and increase performance speed by 60–70 %.

In addition to the reduction in surgical stress due to a reduction in the perceived difficulty of the intervention, it is likely that improved task performance during laparoscopy also would lower complication rates and the necessity for conversion to open surgery. Image quality has gained a major focus in the current laparoscopic field, but the role of depth perception with 3D vision still is underestimated in everyday surgery. The future integration of 3D systems will facilitate the expansion of laparoscopic surgery to more complex interventions and help to advance the field of endoscopically assisted surgery, notably NOTES procedures.

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