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ORIGINAL ARTICLE

Image-based laparoscopic camera steering versus conventional steering: a comparison study

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Abstract

In the last 2 decades, multiple robotic camera holders have been developed to improve camera steering during laparoscopic surgery. A new image-based steering method has been developed for more intuitive camera control. In this article, the efficiency and user experience of image-based steering were compared to conventional steering methods. Four participants (two senior surgical registrars, one junior surgical registrar and a technical medicine student) were enrolled in this study. All participants performed multiple camera steering exercises with three different steering modalities in randomized order: image-based, joystick and manual camera steering. Steering of the laparoscope was evaluated by execution time and with the SMEQ and NASA-TLX questionnaires to analyze user experience. A total of 267 camera steering exercises were performed. The analyzed data showed a significantly shorter execution time for manual camera steering compared to image-based robotic steering ($p = 0.001$) and joystick robotic steering ($p = 0.001$). The participants reported the lowest user experience with joystick camera steering. The results of the questionnaires showed no significant difference in all subscales of user experience for image-based and manual camera steering. Manual camera steering resulted in significantly higher perceived physiological workload scores ($M = 30.0$, IQR = 27.5) compared to image-based ($M = 10$, IQR = 5.0) and joystick camera steering ($M = 15.0$, IQR = 10.0). Manual control of the laparoscope remains the fastest steering method at the expense of a high physical workload. Using image-based camera steering is a viable alternative to the current joystick control of robotic camera holders, as it improves speed and user experience. The study results suggest that optimisation of robotic camera steering with algorithms based on image analysis is a promising technology.

Keywords Laparoscopic camera steering · Laparoscopic camera holder · Image analysis · Computer vision

Introduction

Minimally invasive surgery has become the standard of care for a wide range of surgical procedures [1–6]. As in open surgery, an optimal view of the surgical field is essential in laparoscopic surgery. Despite the significant developments in quality of laparoscopes, surgeons still encounter inadequate visualization of the surgical field on a daily basis [7–9]. The main reason is the fact that camera handling is entrusted to a camera assistant, which is often the least experienced team member in the operating room [10]. Inexperience of the camera assistant can result in more undesired camera movements, failure of centering the surgical field, disruption of the anatomical horizon and increased blurring of the lens, affecting the flow of a surgical procedure [11].

Ideally, the surgeon is in direct control of all laparoscopic instruments, including the camera. Restoring autonomy

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over the laparoscope has shown to improve surgical performance [12, 13]. Multiple active robotic camera holders have been developed to provide surgeons with control of the laparoscope [14–16]. These motorized laparoscopic camera holders have demonstrated utility in providing a stable and controllable view of the operative field, improvement in ergonomics and elimination of the variability in performance [17, 18]. However, these advantages have not resulted in the extensive use and incorporation of these systems in hospitals on a large scale.

The complex steering methods of most active camera holders play an important role in the limited use in laparoscopic surgery. Various controlling interfaces have been tested, including eyeball and head movement tracking, verbal commands, foot switches and joystick controls [14]. These steering methods can be effective, but most interfaces require significant interaction between the surgeon and camera system. Moreover, the surgeon has to perform an extra task during the procedure, which can lead to distraction and might affect the flow of the operation. Developments in image recognition technology have increased the quality and reliability of real-time tracking of surgical instruments. This creates new possibilities for camera steering.

The AutoLap™ (Medical Surgery Technologies, Yokneam, Israel) robotic laparoscopic camera holder has incorporated image analysis for real-time instrument tracking. The visual tracking of surgical instruments is used for intra-operative navigation [19]. This image-guided steering method is activated by a single click on a finger joystick. With this action, the laparoscopic instrument is tagged and continuously tracked, visible to the surgeon with a green bounding box projected on the tip of the instrument of the operating room monitor (Fig. 1b). When the surgeon moves the instrument to the desired working position, the camera is shifted to this position automatically. Minimal interaction between surgeon and robotic camera holder is needed to navigate the camera with this steering method. We, therefore, hypothesized that image-guided steering can improve the performance of robotic camera steering. The aim of this study was to compare robotic image-guided steering with two conventional steering modes (manual and robotic joystick steering) in a laparoscopic phantom study.

Materials and methods

A standard laparoscopic box trainer with custom-made 3D-printed organs was used throughout the study. Approval of the board of directors of the hospital was obtained prior to the study. The AutoLap™ robotic arm was mounted on the side rail of the operating table. Exercises were carried out with a 10 mm 0° laparoscope (Karl Storz, Germany) and a 5 mm grasper. The laparoscope was mounted on the robotic system using disposable plastic clippers. The position of the box trainer, the robotic arm and the monitor were standardized (Fig. 2).

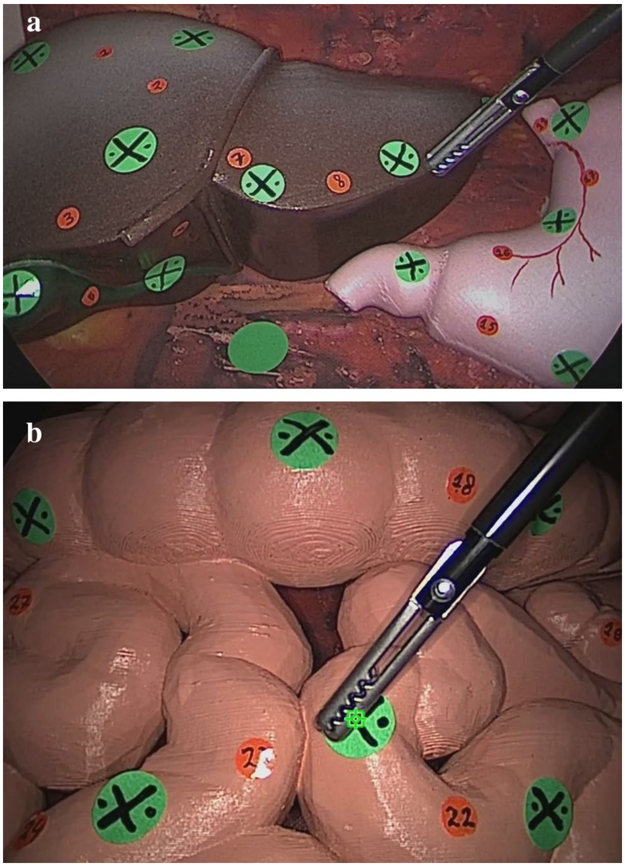

Fig. 1 The navigation exercise along the 3D-printed organ models. **a** The upper abdominal pathway; the liver and stomach model with the markers in green. **b** The lower abdominal pathway; small and large intestine model with the markers in green. The virtual marker of the image-guided mode is visible on the tip of the instrument

Four participants with different levels of laparoscopic surgical experience were included. A student in technical medicine (participant one), a junior registrar (participant two) and two senior surgical registrars (participants three and four) took part in this study. Prior to the study, participants completed a brief training session to familiarize themselves with each steering method. The exercises were performed in sessions to reduce within-subject variability. One session consisted of the execution of the upper and lower abdominal pathways with three different camera steering modes in randomized order: manual steering, joystick steering and image-based steering. A minimum of three and a maximum of six sessions were performed on one day. During the task, the participant was instructed to navigate with the camera along the 14 markers on the upper abdominal pathway (Fig. 1a) and 11 markers on the lower abdominal pathway (1B). To proceed to the next marker, the marker

Fig. 2 The standardized position of the box trainer, the robotic arm and the monitor

on the organ needed to overlap with an additional artificial marker that was placed on the center of the operating room monitor. This was used for standardization and was visually checked by the investigators. Navigation of the camera was executed in a two-dimensional plane (X and Y). The zoom distance (Z) was fixed and could not be controlled by the participants. The goal of the exercise was to execute the camera movements as fast, fluent and accurate as possible.

The primary outcome was task completion time in seconds. The secondary outcome was the subjective user satisfaction, measured with the NASA-Task Load Index (NASA-TLX) and the Subjective Mental Effort Questionnaire (SMEQ). The participants completed the NASA-TLX and SMEQ questionnaires for each steering method after three consecutive sessions to avoid survey fatigue. The SMEQ measures the effort to complete a task on a scale from 0 to 150. The NASA-TLX questionnaire rates the participants' subjective experience by assessing six dimensions (mental demand, physical demand, temporal demand, performance, effort and frustration) on a bipolar scale from 0 to 100. The overall score can be determined by the weighted combination of the six dimensions. However, to reduce between-subject variability, relevance ratings provided by the test subjects were not performed, resulting in the raw TLX score [20].

Statistical analysis was performed using the Statistical Package for Social Sciences (SPSS) 24.0 for Windows. A p value of < 0.05 was considered the threshold for statistical significance. To determine if the data were normally distributed, a Q–Q plot was drafted and the Shapiro–Wilk test for normality was executed. The non-parametric Friedman test with pairwise comparisons (i.e., post hoc testing) was used because both the data of the primary and secondary outcomes were not normally distributed. The Bonferroni adjustment was used to correct for multiple comparisons to decrease the risk of a type I error.

Results

The four participants completed a total of 267 steering exercises. Eighty-nine exercises (33.3%) were performed with joystick steering, 89 (33.3%) with manual steering and eighty-nine (33.3%) with image-based steering. Significant differences were observed in median execution time between the three steering modes (Table 1 and Fig. 3). The fastest steering mode was manual steering with a total median execution time of 45 s, IQR = 8, $p = 0.001$. The median time to complete the laparoscopic task with joystick steering was 121 s, IQR = 22. This was significant slower than the image-based mode with a median execution time of 113 s, IQR = 17, $p = 0.004$.

The median scores of the SMEQ and NASA-TLX questionnaire are displayed in Table 2. The SMEQ questionnaire showed a median score of 40.0 points for joystick steering, 25.0 points for manual steering and 20.0 points for image-based steering. The joystick steering median score was significantly higher than for manual ($p = 0.033$) and image-based steering ($p = 0.016$), which indicates that more effort was used to complete the task. The difference between the median SMEQ scores of manual steering and image-based steering was not statistically significant, $p = 1.000$.

Table 1 Median results and IQR of the execution time (in seconds)

Execution time (seconds)	Participant 1 $N = 32$	IQR	Participant 2 $N = 32$	IQR	Participant 3 $N = 11$	IQR	Participant 4 $N = 14$	IQR	Total median $N = 89$	IQR
Joystick steering	127.00	17	114.00	21	136.00	47	116.00	18	121.00	22
Manual steering	41.50	8	47.00	7	43.00	6	48.00	13	45.00	8
Image-based steering	113.50	8	104.00	9	128.00	25	125.00	14	113.00	17
p value	Joystick/manual	0.001								
	Manual/image-based	0.001								
	Joystick/image-based	0.004								

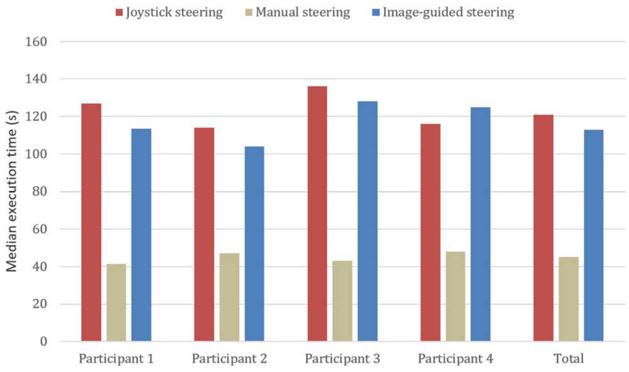

Fig. 3 The median results of the execution time per participant and the overall execution time

The highest median NASA-TLX scores were observed with joystick steering (Table 2). The test subjects rated significantly higher TLX scores on five of the six subdomains for joystick steering compared with the other steering modes, indicating a higher task load. The subgroup analysis of joystick steering and image-based steering showed significant differences for mental demand (25.0 vs 15.0, $p = 0.006$), temporal demand (22.5 vs 20.0 $p = 0.040$), effort (25.0 vs 15.0, $p = 0.005$) and frustration (22.5 vs 12.5, $p = 0.013$) in favor of image-based steering.

On the physical demand domain, a significantly higher score was observed comparing manual steering with joystick steering ($p = 0.007$) and the image-based steering ($p = 0.005$). When comparing manual steering with image-based steering, no significant differences regarding mental demand (12.5 vs 15.0, $p = 0.929$), temporal demand (20.0 vs 20.0, $p = 0.547$), performance (15.0 vs 15.0, $p = 0.759$), effort (20.0 vs 15.0, $p = 0.170$) and frustration (10.0 vs 12.5, $p = 0.170$) were recorded.

Discussion

This study compared a novel image-based laparoscopic camera steering method with manual and joystick controlled laparoscopic camera steering. It is not remarkable that manual camera control results in the shortest task completion time as the speed of robotic camera steering is limited due to safety regulations. The benefits of robotic camera steering are mainly visible as a result of the improved physical workload, a more stable and controlled view and the elimination of variability in camera steering. Within the two robotic steering methods, image-based camera steering showed the most promising results. Image-based steering was significantly faster compared to conventional joystick steering. Moreover, image-based steering had higher rated user experience.

Robotic laparoscopic camera holders provide surgeons full control over their surgical view. However, the additional task of camera navigation with current steering methods requires significant attention of the surgeon and tends to disrupt the flow of the operation. The main reason is that current steering methods only accept simple commands (left, right, up, down, in, out): these commands result in perpendicular movements of the camera in one axis at a time (*X*, *Y* or *Z*). Repositioning of the camera with a joystick can, therefore, be cumbersome, frustrating and time consuming. This is in concordance with our results: joystick control tasks were performed significantly slower compared to conventional manual camera control and image-guided camera steering. Participants reported that controlling the camera with joystick steering was demanding. Image-based camera steering has several advantages compared to joystick steering. First, this steering method requires less interaction of the surgeon with the steering interface. With one click on the joystick, the image analysis algorithm is activated and the camera is positioned to the center of the tagged instrument. Second, the camera moves simultaneously on two axes at a time, resembling manual camera control. Third, tracking

Table 2 Median results of the SMEQ and NASA-TLX questionnaires

	$N = 31$	SMEQ	NASA-TLX					
			Mental demand	Physical demand	Temporal demand	Performance	Effort	Frustration
Joystick steering	Median (IQR)	40.0 (20.0)	25.0 (12.5)	15.0 (10.0)	22.5 (10.0)	25.0 (15.0)	25.0 (12.5)	22.5 (22.5)
Manual steering	Median (IQR)	25.0 (27.5)	12.5 (10.0)	30.0 (27.5)	20.0 (27.5)	15.0 (5.0)	20.0 (15.0)	10.0 (5.0)
Image-based steering	Median (IQR)	20.0 (22.5)	15.0 (10.0)	10.0 (5.0)	20.0 (10.0)	15.0 (17.5)	15.0 (7.5)	12.5 (10.0)
p value	Joystick/manual	0.033	0.005	0.007	0.759	0.002	0.040	0.005
	Manual/image-based	1.000	0.929	0.005	0.547	0.759	0.170	0.170
	Joystick/image-based	0.016	0.006	0.108	0.040	0.067	0.005	0.013

of the instruments ensures surgeons center their working area and will automatically require instruments to remain in sight. In this study, image-based steering outperformed joystick steering in terms of completion time and assessment scores.

The increasing digitalization in the OR and advancements in computer vision have offered opportunities for real-time surgical tool detection and tracking. In 2006, Voros et al. already described the necessity for higher level interactions between surgeon and robotic camera holder [21, 22]. The authors developed image-based software that was able to detect surgical instruments in near real-time, using the insertion points of the instruments. Despite the slow detection rate, the robotic camera holder was able to detect and track surgical instruments without the necessity of marking or modifying the instrument. Ten years later, Zahiri et al. described a prototype of a robotic system with automated camera steering with the intention of replacing the camera assistant [23]. This system was capable of tracking the tip of the instrument and automatically steering the laparoscopic camera. Feasibility was demonstrated in a porcine model and preliminary results were satisfactory.

The further evolution of computer vision has increased the accuracy and robustness of real-time instrument tracking of endoscopic images. Bouget et al. presented an overview of image-based techniques and provided an in-depth comparison of tool detection methods, from image recognition to model learning strategies [24]. They elaborate on the five important components of a surgical tool detection computer vision model: feature extraction, pose estimation, prior knowledge, temporal tracking and optimization techniques. The first step in tool detection is to extract and convert pixel features from an image. The most commonly used features are color features, gradient, texture, shape, depth and motion. Another important part of instrument detection is the utilization of an instrument's pose estimation and the application of prior knowledge. Many detection approaches rely on a set of assumptions to constrain the detection search space, such as tool shape constraints, tool location constraints, user assistance and robotic kinematics. To further obtain a smooth trajectory, measurements can be temporally linked, which is called temporal tracking. Moreover, general optimization strategies such as space reduction and algorithm reduction have been used to allow smooth real-time detection. The image-based steering method of the AutoLap™ system is a computer vision based algorithm and uses the sum of the above approaches in combination with newly developed approaches.

It is evident that the development of computer vision techniques for detection and tracking of instruments is technically challenging. Furthermore, the accuracy is influenced by conditions during surgery [24, 25]. Important factors that affect image quality are motion, blur, variable lighting conditions, specular reflections, shadows and occlusions. Fogging of the scope due to temperature differences or surgical smoke can also reduce the instrument detection rate. Deep-learning algorithms, especially Convolutional Neural Networks (CNNs), have proven to be more robust and effective at tackling these issues [25]. Deep-learning models do not need manual feature extraction and have the ability to learn representations from raw data. In a recent review of the literature, Zang et al. reported on the present papers on CNN's used for image-based tool detection. Experimental results of 19 CNN-based algorithms showed a detection accuracy of 61.5% to 100%. The increasing availability of large publicly available datasets to train and test these networks has had a key role in the development of these algorithms.

To date, the AutoLap™ is one of the only robotic camera holders with real-time instrument tracking possibilities that has reached the market. During this study, we generally noticed an excellent speed of the image-based steering to detect the tip of the instrument in real time. The AutoLap™ detection speed is high enough so that users do not notice any delay. A minimum frame rate of around 30 to 60 frames per second is generally considered high enough and it can be perceived as fluent motions if no frame drops occur [26, 27]. There are, however, some disadvantages of the current image-based steering method. Ideally, the camera is repositioned on all axes at the same time (*X* and *Y*), maintaining the same zoom distance between the laparoscope and the tissue (*Z*). However, with the current algorithm, the camera is repositioned on the *X* and *Y* axes but not on the Z axis. Future 3D navigation of the camera would be beneficial and would make it even easier to steer the camera. In addition, the accuracy of the image-based steering mode is still not flawless and errors in detection are unavoidable [19]. Usually, this could be adjusted quickly, but it results in an extra action as repositioning of the camera has to be performed again. There are several limitations to be mentioned. First is the ex-vivo design of the study. In this study, all exercises were conducted in an artificial laboratory setting with standardized optimal conditions. As mentioned before, it must be addressed that the image detection rate will be affected by image quality. Therefore, performing this experiment in vivo could affect the accuracy and execution time. Furthermore, this study was limited by its relatively small sample size. Although we found significant differences in median execution time, future validation with studies of larger sample sizes is needed. Another potential bias in this study is the method of checking the overlap of the markers, which was visually done by the investigators. Objectively measuring by determining the actual position of the center viewpoint of the camera and the position of the markers with, e.g., AI could potentially eliminate this bias [28].

With further evolution, real-time instrument detection and tracking image analysis has the potential to improve camera steering. This technology could possibly be integrated into existing robotic platforms to enhance usability and performance of robotic camera steering. With further use of autonomous anatomical scene understanding, it would even become possible to recognize certain actions. Action recognition could be used in the realization of autonomous camera control. An example where autonomous camera control would be beneficial is in laparoscopic suturing: autonomous decreasing camera distance when suturing and increasing camera distance when tying the knot. With the addition of these applications, image-based steering may be able to outperform human camera steering in the future.

Conclusion

This study shows that image-based steering is superior to conventional joystick steering in terms of execution time and subjective user experience. Robotic image-based control of the laparoscope is a promising technology. With image quality and artificial intelligence technology, rapidly evolving, more image-based applications will be possible in the future.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11701-021-01342-0.

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Declarations

Conflict of interest P.J.M. Wijsman was a Clinical Field Engineer of Medical Surgery Technologies ltd (MST) from 2016 to 2018. I.A.M.J. Broeders is a consultant for Johnson & Johnson and Intuitive Surgical. F.J. Voskens, L. Molenaar and C.D.P. van't Hullenaar have no conflicts of interest or financial ties to disclose.

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