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Effect of Visual Display Location on Human Performance in Simulated Laparoscopic Tasks

Hernandez R[1], Travascio F[1], Onar-Thomas A[2] and Asfour S[1]

[1]*Industrial Engineering Department, 1251 Memorial Drive, McArthur Engineering Building, University of Miami, Coral Gables, FL 33124, USA*
[2]*St. Jude Children's Research Hospital Department of Biostatistics, St. Jude Children's Research Hospital, 262 Danny Thomas Place, Mail Stop 768, Memphis, TN 38105, USA*

Abstract

Laparoscopy is a minimally invasive surgery practiced through small incisions in the body, and requiring the use of long-reach instruments and a camera. Since the video feed is displayed on a monitor, depth perception can be significantly altered, and it is hypothesized that such alterations may depend on the relative position of the monitor with respect to the operator. The objective of this study was to explore the relationship between monitor positioning and human performance in laparoscopic tasks.

A total of eight male subjects volunteered to perform a variety of simulated laparoscopic tasks including object transfers, precision cutting, and suturing while three different monitor configurations were used (i.e., left, center, and right of the user). Tool trajectory was monitored using a motion capturing system, and task performance was evaluated using human performance quantitative metrics including completion time, depth of penetration, path length, axial speed, and motion smoothness. Results showed that human performance significantly increased when monitor location was centered with respect to the user during precision cutting. Moreover, subjects' performance decreased when the monitor was placed on their dominant-hand side. The findings of this study suggest ergonomic guidelines for optimizing human performance in simulated and actual laparoscopic tasks. Specifically, placing the monitor in a central position with respect to the user should represent the standard configuration while conducting laparoscopy.

Keywords: Laparoscopy; Performance metrics; Monitor position; FLS trainer; EoSim

Abbreviations: FLS: Fundamentals of Laparoscopic Surgery

Introduction

Laparoscopy is a type of minimally invasive surgery performed through small incisions in the abdomen or pelvis; it is the most common operation for cholecystectomy [1], with close to 700,000 of these procedures performed each year [2]. Since surgeons cannot use their hands directly to operate as in open surgery, long-reach instruments are required to perform laparoscopy. Furthermore, to compensate for the lack of direct vision inside the body, a small camera needs to be inserted. The video feed is then displayed on an external monitor, giving the surgeon the necessary vision to perform the operation. This type of remote viewing significantly alters depth perception [3], adding to the challenge of maneuvering laparoscopic instruments during a procedure. Therefore, concerns about a surgeon's performance in laparoscopy due to the effects of visual configuration have motivated significant research in this area [4-7].

Laparoscopy studies rely predominantly on "box" simulators, as opposed to actual operations, to assess performance under different monitor configurations. The use of simulators is not only the most feasible method for large experimental designs, but it also has direct relevance to the field of laparoscopy. In fact, the Fundamentals of Laparoscopic Surgery (FLS) certification exam [8], which has become the standard for laparoscopic evaluation, consists of completing a variety of basic tasks under specific performance criteria, using the FLS Trainer System (VTI Medical, Waltham, MA), (Figure 1).

Previous studies in laparoscopy have focused on exploring the effects of monitor placement on occupational safety and task performance by varying monitor position, elevation, and orientation relative to the surgeon [4-7,9,10]. In regards to optimal monitor configuration, research focused on safety shows conflicting results when compared to that of performance. For instance, ergonomics studies suggest that the monitor should be placed at the eye-level height, to reduce discomfort for the surgeon due to excessive neck flexion [7,9]. On the other hand, studies focusing on performance have indicated that the monitor should be placed closer to the operating surface, with eyes gazing down at the screen, for faster completion times [4,6]. Nonetheless, there is a general indication in the literature that the optimal orientation of the monitor is directly in front of the surgeon, as opposed to the sides, resulting in greater comfort and performance overall [5].

Although there is compelling evidence to suggest an effect of monitor position in laparoscopic performance, there are some common limitations imposed in the experimental designs of previous studies that lead to further inquiry. For one, studies rely exclusively on object transferring tasks designed by the particular research team [5,6], without using the official transferring task provided by the FLS Trainer System, which is used in the FLS exam. This not only excludes a variety of transferring tasks, such as those requiring simultaneous instrument coordination, but other types of fundamental laparoscopic tasks as well, such as precision cutting and ligating loop tying, which are required for FLS certification [11]. Furthermore, previous work

***Corresponding author:** Shihab Asfour, College of Engineering, University of Miami, 1251 Memorial Drive, MEB 268, Coral Gables, FL 33124-0621, USA, Tel: +1-(305)-284-2367; Fax: +1-(305)-284-4040; E-mail: sasfour@miami.edu

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has focused predominantly on measuring task completion time to evaluate laparoscopic performance with simulators [4-7]. However, a more comprehensive assessment of proficiency incorporates a variety of other performance metrics related to the quality of motion of the instrument tips [12,13]. For instance, evaluating the movement of the instruments could reveal the presence of abrupt movements that lead to greater risk of tissue-tearing in an actual surgical procedure, regardless of how fast the task was completed [13].

Overall, based on previous results regarding optimal monitor placement, it is expected that across all tasks and metrics, placing the monitor directly in front of the user will lead to significantly better performance as opposed to placing it on the sides (Figure 1) [4-7]. Moreover, if the monitor is placed on the user's dominant-hand side, results should show a significant detriment of task performance compared to other positions [5]. Therefore, the objective of this study is to verify if these observations hold true when other clinically relevant laparoscopic tasks are executed, and when metrics other than completion time are used to evaluate user performance.

Materials and Methods

Participants

The procedure and methods used in this study were approved by the Internal Review Board (IRB) at the University of Miami. Subjects signed a consent form before participating in the study.

Eight adult male volunteers participated in this study. As part of the inclusion criteria, all participants had no previous experience in laparoscopic procedures, with the assumption that it would enhance the performance contrast between different monitor configurations. Furthermore, each person was right-handed and had normal or corrected-to-normal vision.

Materials

Subjects performed the following simulated tasks provided by the FLS Trainer System, which are also used in the FLS certification exam: "Peg Transfer," "Precision Cutting," and "Ligating Loop" [11], (Figure2) Additionally, the "Object Transfer" task from the eoSim (eoSurgical, Edinburgh, Scotland) was included in the study, a transfer task requiring simultaneous instrument coordination, shown to be equivalent to the "Peg Transfer" task of the FLS system in measuring laparoscopic proficiency [12] . The eoSim system (Figure 1).

The FLS simulator camera was connected to a 23" external monitor mounted on a tripod, providing mobility and allowing for proper ergonomic adjustment of its height with respect to the subject's eye level. In addition, the mobility provided by the tripod helped to maintain the optimal 0.6m distance from the user's eyes as suggested in recent studies [9]. A height-adjustable table provided an optimal work position for the arms when adjusted based on the user's elbow height [10]. The experimental setup is shown in (Figure 1). A chair placed nearby the workstation provided rest to the participants if they felt tired between tasks.

Reflective markers were placed on the laparoscopic instruments, (Figure 3), to capture their movement in three-dimensional space using a Vicon motion capturing system (Vicon Motion Systems Ltd, UK) with 10 surrounding infrared cameras. The movement of the instrument tips, however, was later derived based on the recorded position of the outer markers, by way of a geometric translation, since the markers at the tips became obscured from camera-view due to the simulator box.

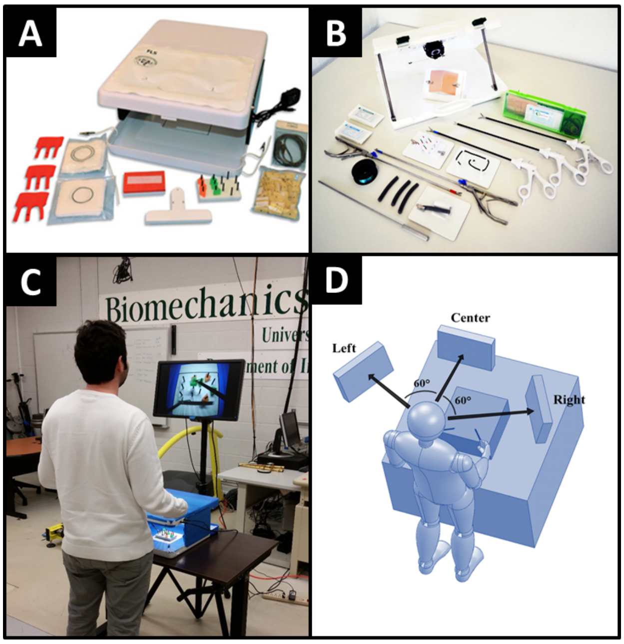

Figure 1: Experiment equipment and setup: (A) FLS Trainer System, (B) eoSim, (C) experimental setup, and (D) illustration of monitor positions.

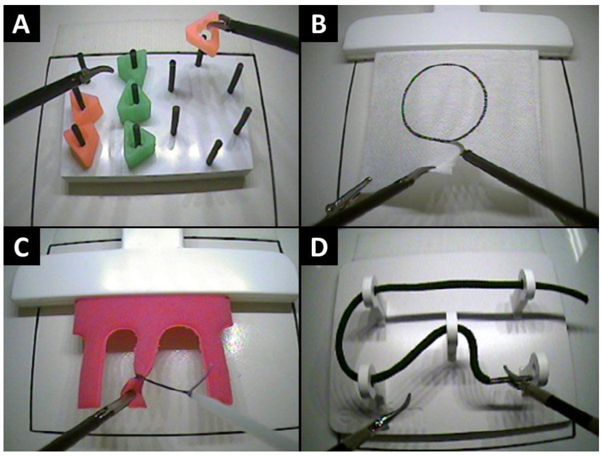

Figure 2: Laparoscopy training modules: (A) FLS "Peg Transfer," (B) FLS "Precision Cutting," (C) FLS "Ligating Loop", and (D) eoSim "Object Transfer."

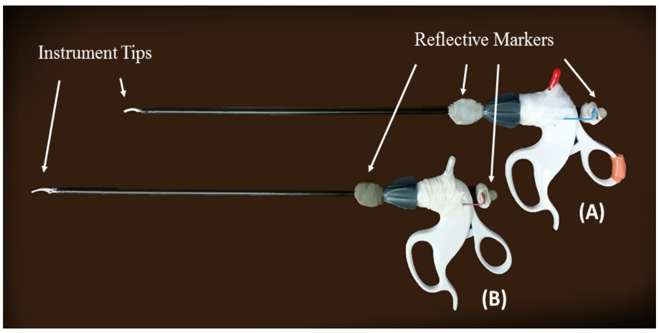

Figure 3: The two kinds of laparoscopic instruments used in the study along with attached reflective markers: (A) endoscopic scissor, and (B) grasper.

Performance metrics

Completion time: Length of the time it takes to complete a single task, from start to finish.

Path length: Total combined path distance followed by the laparoscopic instruments [13].

Motion smoothness: Third time-derivative of position of the combined instruments, averaged across trial. This metric provides a measure of the abrupt changes in acceleration of the instrument tips, with higher values corresponding to jerkier movement [13].

Depth: Total path length traveled by both instruments in the axial direction.

Average axial speed: Average speed of instrument tips in the axial direction. This metric is used for the study as a measure of "puncturing propensity," since faster movements in the axial direction can lead to tissue damage in actual laparoscopic surgery [14].

Experimental design

The experiment consisted of a completely randomized 4x3 blocked factorial design with three repeated measures, blocking by subject. Thus, a total of 36 trials were performed by each subject. The trial order was spread evenly across four sessions within a three week period to avoid effects of fatigue. The independent variables were monitor location and laparoscopic task. The monitor locations were directly in front of the user, and at a 60° angle towards the left and right sides, following the Haveran et al. [5] setup, (Figure 1). The tasks performed were the "Peg Transfer," "Precision Cutting," and "Ligating Loop" tasks provided by the FLS Trainer, along with the "Object Transfer" task from the eoSim.

The dependent variables measured were Task Completion Time, Path Length, Average Motion Smoothness, Depth, and Average Axial Speed. For the FLS "Ligating Loop" task, only the Completion Time was measured. Subjects were treated as a random factor. Furthermore, the order of trials for each task was included as a covariate factor in the model, to account for the effect of a learning curve. The following model was used, where μ stands for the mean value controlling for the other factors in the model, and *e* stands for variations due to sources of error:

Performance Metric = μ + Subject + Monitor + Task + Monitor x Task + Trial Order + *e*

Procedure

Participants first became acquainted with the simulator tasks in a short training session, which consisted of guided practice runs. During training, the monitor was placed in front of the subjects at the workstation height and at a tilt angle of 20°, which corresponds to one of the monitor configurations used in Hanna et al. and Rogers et al. [4, 6]. During the actual experiment, however, the monitor height was raised to the subject's eye level to ensure proper ergonomic positioning [9], and the monitor location changed depending on the randomized trial order assignment. Training ended when subjects displayed a clear understanding of the requirements for each task, as well as being able to complete them within the maximum allotted time for both the FLS certification exam [11] and the eoSim guidelines [15]. However, during the actual experiment, trials that exceeded the maximum allotted completion times were not discarded and were included in the data analysis. The task procedures were based on the instructions provided by the respective manuals [11,15] as outlined below.

For the FLS "Peg Transfer," subjects used two graspers to first transfer six objects from the left to right-hand side of a peg board and then transfer all of them back to the left side. Each object was transferred in midair to the other grasper in the direction of transferring, without using the pegs or board for assistance, and dropped on an empty peg. There was no importance placed on the order of the transfer. In the event that a subject dropped a retrievable object within the field of view, they were allowed to pick it up and continue the trial, otherwise the trial was discarded since they could no longer complete this task. Timing began when subjects grasped the first object and ended upon release of the last object. The maximum allotted time was five minutes for this task.

The eoSim "Object Transfer" task consisted of passing a shoelace through five loop pegs in a predetermined order, using a left and right grasper. No restriction was placed on how the string was manipulated. Timing began upon first grasp of the string, and the maximum allotted time for this task was seven minutes.

The FLS "Precision Cutting" task consisted of cutting along the stamped circle on a 4"x4" two-ply piece of gauze, suspended and taut with a clip. Subjects were required to cut the circle using a right endoscopic scissor, and use a left grasper to assist them in the process. The cut started from the bottom edge of the gauze, rather than directly cutting into the material. As opposed to the FLS guidelines [11], subjects were not allowed to exchange instruments at any time, to control for effects of handedness, having them use only their right hand for the cutter. Timing began upon first grasp of the gauze, and the maximum allotted time for the cutting task was five minutes.

Lastly, the FLS "Ligating Loop" required subjects to place and secure a reusable endoloop knot around the middle appendage of a foam organ at the provided mark. A left grasper first went through the loop to securely grab the tip of the appendage, and then using their right hand, subjects slipped the endoloop over the appendage and tightened it around the black mark. Afterwards, subjects released the left grasper and simulated a cut by grasping the string above the endoloop knot. Timing began when subjects moved either instrument to start the task and ended with the simulated cut on the string. The maximum allotted time for this task was three minutes.

Data analysis

The collected motion capture data was post-processed using MATLAB (v2013m Natick, MA) to calculate the performance metrics. A Butterworth filter was applied before taking the average of the motion smoothness values, in order to reduce the inherent noise when calculating higher order derivatives. Data processing and statistical analysis was performed in Minitab 17 (v2013 State College, PA). A natural logarithmic transformation was applied to the response variables when appropriate, to improve model fitting.

A two-way analysis of variance (ANOVA) with repeated measures was performed to evaluate the effects of monitor position and task on each performance metric. Additionally, a one-way ANOVA with repeated measures was performed on each task and performance metric to identify any task-specific monitor effects. The between-subject effects were controlled for in the model via blocking by subject, while the effects of the learning curve were controlled by including the trial order number as a predictive factor in the model.

A p-value of <0.05 was considered significant. When monitor position as a factor in the model was found significant, a pairwise comparison with a Tukey test was then performed to identify which monitor position had significantly different values.

Results

The values for the means and standard deviations for each performance metric, task, and monitor location are summarized in Table 1. It was noted that the values for the Depth and Path Length metrics were virtually identical to each other for all tasks in the study. The boxplots in (Figure 4) provide an illustration of the distribution of the data collected in the experiment. Some of the raw data points appeared as outliers, but they were not excluded, since no experimental reason was present to justify their exclusion. Furthermore, the residuals did not indicate any issue with the fitted models after applying a logarithmic transformation to the response variable in question.

The two-way repeated measures ANOVA models involving task and monitor placement did not reveal a significant effect on performance due to monitor placement.

Monitor positioning was significant when performing the one-way repeated measures ANOVA, but only on the FLS "Precision Cutting" task for the Depth, (p = 0.046), and Path Length metric, (p = 0.040), Tables 2 and 3. After applying a pairwise Tukey test for the Depth in the cutting task, as shown in Table 4, the right monitor had significantly higher values when compared to the center monitor (+1.248 meters, p = 0.036). Similar results were found for the Path Length in the cutting task, between the right and center monitor (+1.251 meters, p = 0.031), Table 5.

Discussion

Based on the results obtained in this study, none of the three monitor configurations led to statistically significant differences in completion time for any of the selected tasks. Interestingly, the two transfer tasks which have direct relevance to the type of task chosen in the literature did not show a significant trend consistent to previous research results. However, of note is that previous monitor studies used transferring tasks designed by the research team, focusing on smaller

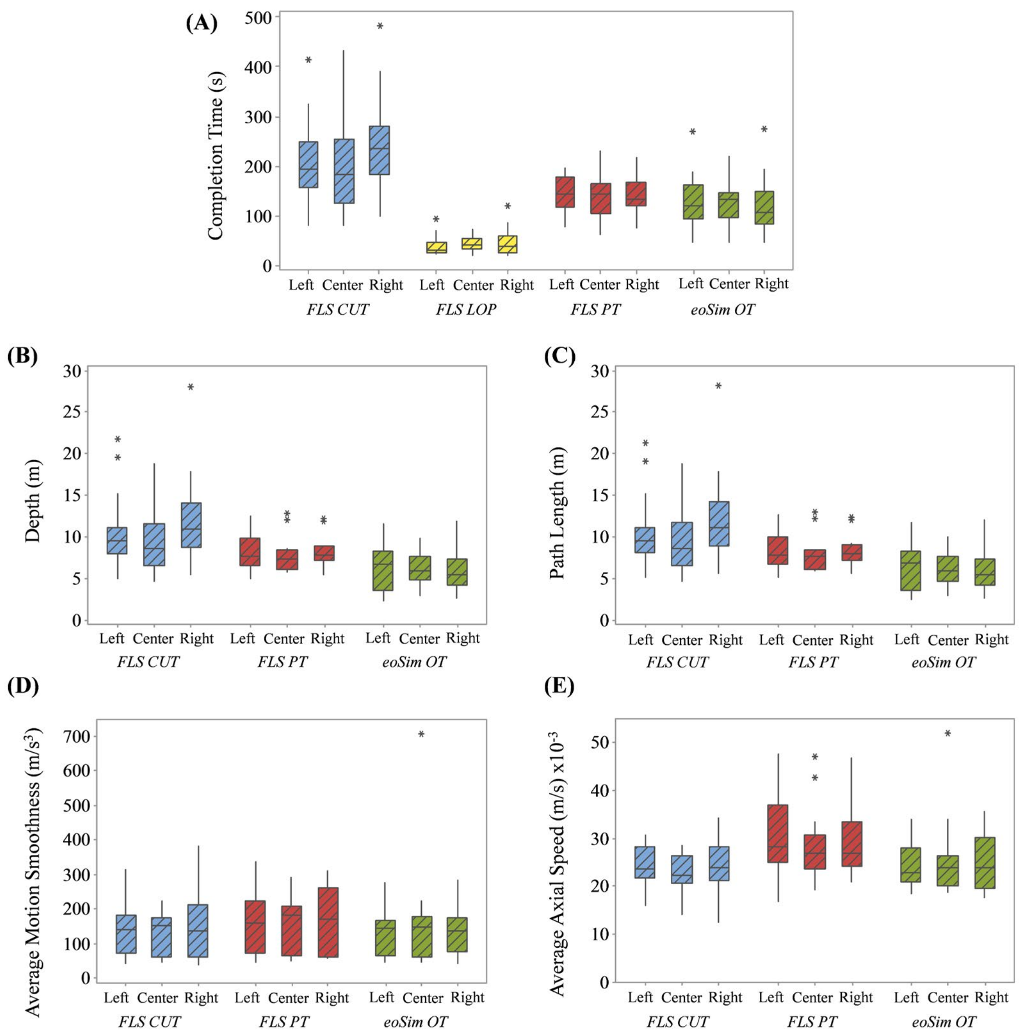

Figure 4: Boxplots of the raw data for each performance metric, task, and monitor location. (A) Completion Time, (B) Depth, (C) Path Length, (D) Average Motion Smoothness, and (E) Average Axial Speed. (CUT) Precision Cutting, (LOP) Ligating Loop, (PT) Peg Transfer, and (OT) Object Transfer.

		Monitor		
		Left	Center	Right
Metric	Task	Mean ± STD	Mean ± STD	Mean ± STD
Completion Time (s)	**FLS CUT**	207.9 ± 77.2	204.9 ± 93.9	238.5 ± 87.7
	FLS PT	143.6 ± 37.4	142.1 ± 45.8	137.8 ± 34.7
	eoSim OT	128.1 ± 49.3	123.7 ± 39.9	118.3 ± 51.1
	FLS LOP	36.9 ± 17.4	42.8 ± 13.1	46.3 ± 25.9
Path Length (m)	**FLS CUT**	10.3 ± 3.8	9.4 ± 3.5	11.9 ± 4.9
	FLS PT	8.4 ± 2.3	7.9 ± 2.2	8.2 ± 1.7
	eoSim OT	6.5 ± 2.6	6.1 ± 2.0	6.0 ± 2.7
Depth (m)	**FLS CUT**	10.3 ± 3.9	9.4 ± 3.4	11.8 ± 4.9
	FLS PT	8.3 ± 2.3	7.8 ± 2.2	8.1 ± 1.7
	eoSim OT	6.4 ± 2.6	6.1 ± 1.9	5.9 ± 2.6
Average Motion Smoothness (m/s^3)	**FLS CUT**	135.0 ± 67.4	134.1 ± 61.6	146.6 ± 85.1
	FLS PT	160.7 ± 82.3	165.7 ± 79.1	167.9 ± 92.3
	eoSim OT	136.5 ± 68.3	159.8 ± 138.5	140.5 ± 68.2
Average Axial Speed (m/s) x 10^{-3}	**FLS CUT**	24.2 ± 4.1	22.6 ± 4.1	24.8 ± 5.6
	FLS PT	30.8 ± 8	28.8 ± 7.8	29.9 ± 7.5
	eoSim OT	24.6 ± 4.9	25.0 ± 7.3	24.9 ± 5.6

Table 1: Means and standard deviations of the collected data, for each performance metric, task, and monitor location. (CUT) Precision Cutting, (LOP) Ligating Loop, (PT) Peg Transfer, and (OT) Object Transfer.

Source	df	F	p
Monitor	2	3.25	.046*
Subject	7	3.43	.004**
Trial Order	1	20.43	.000**
Error	55		
Total	65		

Table 2: Repeated measures one-way ANOVA summary for Depth metric in FLS “Precision Cutting” task. *p<0.05 and **p<0.01 significant.

Source	df	F	p
Monitor	2	3.40	.040*
Subject	7	3.46	.004**
Trial Order	1	20.35	.000**
Error	55		
Total	65		

Table 3: Repeated measures one-way ANOVA summary for Path Length metric in FLS “Precision Cutting” task. *p<0.05 and **p<0.01 significant.

scale transfers [5], rather than using predesigned simulator modules that are more complex and take longer to complete.

In regards to the other performance metrics used in this study, there was no statistically significant relationship between the monitor locations across most tasks, except during the precision cutting task. Some basic laparoscopic operations may be more susceptible to the effects of monitor position than others. Specifically, the results in this study suggest that tasks requiring greater precision could be more sensitive to changes in display configuration.

In terms of the performance metric selection for this study, only the Depth and Path Length were affected significantly due to monitor placement. These two metrics are related to the user’s mastery of the task space [12] and have been used successfully to compare performance among groups in several studies [16-18]. As mentioned previously in regards to the precision cutting task, the amount of movement associated with these metrics was found to be higher for the dominant-hand side monitor compared to that of the center. Additionally, it was noted that the values for the Depth and Path Length were almost identical to each other across all tasks. Based on the definition of these two metrics, their values indicate that the selected laparoscopic tasks for the study did not reflect a perceivable difference between axial and rotational movements of the instrument tips. Therefore, the Depth and Path Length may not be independent measures when assessing performance in laparoscopic tasks that are short in duration.

The use of inexperienced subjects imposed a limitation on the study, when considering that real-life laparoscopic procedures are performed by experienced surgeons who are the intended target group for these monitor studies. However, our focus was to investigate the effects on innate human depth perception capabilities due to changes in the monitor configuration, as opposed to focusing on a specialized group of experienced users. This also introduces the learning curve as a potential source of variance. In order to mitigate the effect of learning on the outcomes of the study, our experimental design used within-subject trial randomization and included trial order in the ANOVA model. Performing a similar experiment with experts in laparoscopy might provide different results than those found in this study, and will be investigated in future research. Additionally, this study did not explore the effect of monitor location on quantitative measures of precision, nor on its accountability for task mistakes. Analysis methods used to evaluate task precision and mistakes, such as those found in Kowalewski et al., 2014 [19], will be object of a future study. Further experimentation could also be performed in order to explore tasks that require longer completion times than those used in this study. They may not only reveal a higher contrast in performance between monitor configurations, but also provide closer resemblance to the duration of actual surgical procedures.

Overall, the results found in this study did not reveal a statistically significant difference between the three monitor configurations across

Monitor Position Comparisons	Difference of Means (meters)	Standard Error of Difference (meters)	95% Confidence Interval for Mean		Adjusted p-value
			Lower Bound (meters)	Upper Bound (meters)	
Center – Left	0.875	1.091	0.710	1.080	0.284
Right – Left	1.093	1.086	0.897	1.332	0.530
Right – Center	1.248	1.091	1.012	1.540	0.036*

Table 4: Pairwise comparison Tukey test for the Depth metric between monitor positions in the FLS “Precision Cutting” task, converted back to meters from the natural log transformation values. *p<0.05 and **p<0.01 significant.

Monitor Position Comparisons	Difference of Means (meters)	Standard Error of Difference (meters)	95% Confidence Interval for Mean		Adjusted p-value
			Lower Bound (meters)	Upper Bound (meters)	
Center – Left	0.874	1.090	0.710	1.075	0.266
Right – Left	1.093	1.084	0.899	1.329	0.518
Right – Center	1.251	1.090	1.017	1.540	0.031*

Table 5: Pairwise comparison Tukey test for the Path Length metric between monitor positions in the FLS “Precision Cutting” task, converted back to meters from the natural log transformation values. *p<0.05 and **p<0.01 significant.

most tasks and performance metrics. Monitor placement had a more prominent effect on performance in the precision cutting task. From a design perspective, we recommend not placing the monitor on the user’s dominant-hand side when performing tasks that require greater accuracy and precision, since it can result in unnecessary movement inside the operating space. Placing the monitor directly in front of the user is the most preferable configuration for this kind of operation. Hence, in accordance to data trends found in this study as well as previous research findings, and although the effect of monitor placement was not found significant for the other tasks, centering the monitor with respect to the user is recommended during all laparoscopic exercises. This monitor configuration should represent an ergonomic standard for maximizing human performance in laparoscopic procedures.

Although centering the monitor is the recommended configuration for laparoscopic task performance, possible implications for this setup should be considered, such as its practicality in actual surgical operations. Therefore, limitations provided by the operating room could affect the significance of this kind of study, where there could be a limited choice for monitor placement. Nonetheless, the use of a center monitor should not only become the standard for actual practice, but also the ideal configuration from which to compare different research protocols and aims.

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