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COGNITIVE LOAD ASSESSMENT IN LAPAROSCOPIC SURGERY: PHYSIOLOGICAL CORRELATES AND PERFORMANCE METRICS

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Abstract

Background: Laparoscopic surgery, known for its minimally invasive approach, imposes significant cognitive demands on surgeons due to precise coordination and instrument manipulation. Understanding physiological markers like heart rate variability (HRV) and pupil dilation is crucial for optimizing surgical training and performance. Despite research in other fields, studies in laparoscopic surgery are limited. This study analyzes HRV, pupil dilation, electrodermal activity (EDA), and electroencephalography (EEG) to better understand cognitive demands and enhance surgical outcomes. **Materials and Methods:** This cross-sectional study, conducted in a tertiary care facility in Jharkhand over one year, recruited 25 experienced laparoscopic surgeons. The LapSim® simulator replicated a realistic surgical environment, integrated with physiological sensors including HRV, pupil dilation, EDA, and EEG. Descriptive statistics, correlation analysis, and multivariate regression models were employed to examine relationships between cognitive load and physiological responses using SPSS version 20.0 software. Pearson correlation coefficients were calculated with significance set at $p < 0.05$. **Result:** The study included 25 experienced laparoscopic surgeons (mean age 42.5 ± 5.2 years, mean experience 12.8 ± 3.6 years), predominantly male (72.0%). Predictor variable analysis revealed significant associations with cognitive load, notably HRV ($\beta = 0.52$, $p < 0.001$) and EEG power ($\beta = 0.67$, $p < 0.001$). Cognitive load scores differed across tasks, with camera control having the highest (73.6 ± 2.5) and tissue retrieval the lowest (64.5 ± 3.2). Correlation analysis revealed significant associations between cognitive load and physiological parameters, notably HRV ($R = 0.72$, $p < 0.05$) and EEG power ($R = 0.61$, $p < 0.05$), but not EDA ($R = -0.21$, $p > 0.05$). **Conclusion:** These findings offer insights for refining surgical training and performance assessment protocols, with the potential to enhance patient safety and surgical outcomes.

INTRODUCTION

Laparoscopic surgery has revolutionized the field of minimally invasive surgical procedures by offering patients reduced post-operative pain, shorter recovery times, and improved cosmetic outcomes compared to traditional open surgeries.[1] Despite these benefits, laparoscopic surgery demands significant cognitive resources from surgeons due to the complex hand-eye coordination, spatial orientation, and precise instrument manipulation required.[2]

Cognitive load, a concept originating from cognitive psychology, refers to the mental effort required to perform a task.[3] In laparoscopic surgery, cognitive load can stem from various sources, including the need to interpret 2D visual representations of a 3D surgical field, coordinate movements between multiple instruments, and make rapid decisions in dynamic and often stressful situations.[4] Understanding the physiological correlates of cognitive load in laparoscopic surgery is essential for optimizing training programs, designing ergonomic operating environments, and developing support systems to enhance surgical performance and patient safety.[3,4]

Several physiological measures have been proposed as indicators of cognitive load, including heart rate variability (HRV), pupil dilation, electrodermal activity (EDA), and changes in cortical activity as measured by electroencephalography (EEG). HRV reflects the autonomic nervous system's regulation of heart rate and has been shown to decrease with increased cognitive load. Pupil dilation is associated with changes in arousal and mental effort, while EDA reflects sympathetic nervous system activation in response to stressors. EEG provides direct insight into cortical activation patterns associated with different cognitive tasks.[5,6]

Previous research has investigated the physiological correlates of cognitive load in various domains, including aviation, driving, and educational settings. However, studies specifically focusing on laparoscopic surgery are limited.[7-9] Given the unique cognitive demands and high-stakes nature of laparoscopic procedures, investigating the physiological markers of cognitive load in this context is crucial for advancing surgical training and performance optimization.

This study aimed to analyze the physiological correlates of cognitive load in laparoscopic surgery using a combination of objective measures, including HRV, pupil dilation, EDA, and EEG. By identifying reliable physiological markers of cognitive load, this study seemed to enhance our understanding of the cognitive demands of laparoscopic surgery and inform the development of targeted interventions to support surgeon training and performance in this challenging surgical modality.

MATERIALS AND METHODS

Study design and study Participants: The present cross-sectional study was conducted in tertiary care of Jharkhand, for a period of 1 year from January 2022 to December 2022 after obtaining the Ethical approval from the Intuitional ethics committee. A total of twenty-five experienced laparoscopic surgeons were recruited for this study from various super speciality centres of Jharkhand using convenient sampling technique. Inclusion criteria encompassed surgeons with a minimum of three years of experience in performing laparoscopic procedures regularly, with proficiency demonstrated through board certification or equivalent qualifications. Exclusion criteria were meticulously defined to exclude participants with any history of neurological or psychiatric disorders, substance abuse, or medications known to affect cognitive function or physiological responses. Additionally, individuals with color blindness or any ocular conditions potentially impacting pupil dilation measurements were excluded. Prior to participation, all recruited surgeons underwent a comprehensive screening process, including medical history review and physical examination, to ensure eligibility. Informed consent was obtained from each participant, outlining the study's objectives, procedures, potential risks, and confidentiality measures.

Experimental Setup and physiological monitoring

The experimental setup was meticulously designed to replicate a realistic laparoscopic surgical environment while enabling comprehensive physiological monitoring. A state-of-the-art laparoscopic surgical simulator, the LapSim® platform (Surgical Science, Gothenburg, Sweden), served as the core component of the setup. The LapSim® simulator is renowned for its fidelity in replicating laparoscopic procedures and providing realistic haptic feedback.

The simulator featured an ergonomic surgical console equipped with foot pedals and hand controls, mimicking those found in actual operating rooms. A high-definition display monitor positioned in front of the console provided visual feedback, displaying the simulated surgical field captured by an integrated camera system. The camera system comprised multiple high-resolution cameras positioned strategically to simulate various laparoscopic views, including the primary and secondary trocar sites.

To enable comprehensive physiological monitoring, a suite of sensors was seamlessly integrated into the LapSim® simulator. These sensors included:

Heart Rate Variability (HRV): A chest strap equipped with a photoplethysmography sensor (CardioPulse™ Sensor, BioSensorsTech, United States) was utilized to capture continuous heart rate measurements. The sensor transmitted data wirelessly to a dedicated monitoring unit for real-time HRV analysis.

Pupil Dilation: An infrared eye-tracking system (OptiTrack™ Eye Monitor, NeuroGaze Solutions, Canada), comprising specialized cameras and software algorithms, was integrated into the simulator to capture and analyze changes in pupil diameter. The system offered high spatial and temporal resolution, allowing precise measurement of pupil dynamics during simulated surgical tasks.

Electrodermal Activity (EDA): Sensors for electrodermal activity (SkinSync™ EDA Sensors, DermSense Innovations, Germany) were affixed to participants' fingertips using biocompatible adhesive patches. These sensors measured changes in skin conductance levels, providing insights into sympathetic nervous system arousal responses.

Electroencephalography (EEG): A wireless EEG headset (MindSync™ EEG Headset, CortexWave Technologies, Australia), featuring multiple electrodes conforming to the international 10-20 system, was worn by participants during experimental sessions. The EEG headset facilitated non-invasive monitoring of cortical activity, enabling the capture of event-related potentials and spectral power changes associated with cognitive load.

Prior to data collection, all sensors underwent calibration and validation procedures to ensure accuracy and reliability. Additionally, participants received detailed instructions on sensor placement and simulator operation to minimize potential confounders. Throughout the experimental sessions, a dedicated research team monitored the functioning of physiological sensors and provided technical support as needed.

The cognitive load was calculated using a combination of physiological measures including heart rate variability (HRV), pupil diameter, electrodermal activity (EDA), and electroencephalography (EEG). HRV, pupil diameter, and EDA were analyzed for changes indicative of cognitive load, with decreased HRV, increased pupil diameter, and heightened EDA associated with higher cognitive load. EEG data was processed to identify patterns of brainwave activity linked to cognitive load. These measures were integrated using multivariate regression analysis techniques to develop a composite cognitive load score.

Statistical analysis: Upon completion of data collection, a rigorous analysis was conducted to elucidate the relationship between cognitive load and physiological responses during laparoscopic surgery. Physiological data, encompassing heart rate variability (HRV), pupil dilation, electrodermal activity (EDA), and electroencephalography (EEG) signals, were subjected to comprehensive statistical analyses using SPSS version 20.0 software. Initial examination involved computing descriptive statistics, including mean, standard deviation, and range, to characterize the distribution and variability of physiological parameters across different surgical tasks and cognitive load levels. Correlation analyses were performed to assess the associations between cognitive load measures and physiological responses. Pearson correlation coefficients were calculated to quantify the strength and direction of relationships between variables and were considered statistically significant if p was <0.05.

RESULTS

The study involved experienced laparoscopic surgeons with a mean age of 42.5 years (±5.2 SD) and an average of 12.8 years of surgical experience (±3.6 SD). Male participants constituted 72.0% (n=18), while females comprised 28.0% (n=7). General surgery was the predominant specialty (64.0%, n=16), followed by gynecology (24.0%, n=6) and urology (12.0%, n=3). Right-handedness was prevalent (88.0%, n=22), with fewer left-handed (8.0%, n=2) and ambidextrous (4.0%, n=1) surgeons [Table 1].

In our study, the trocar placement exhibited a mean HRV of 75.2 ms (±3.5 SD), with comparable patterns observed in Tissue Dissection (69.8 ± 3.2 ms) and Suturing Practice (72.5 ± 3.0 ms). Pupil diameter fluctuated within a narrow range across tasks, with Clip Application displaying the largest average diameter (4.6 ± 0.4 mm) and Tissue Dissection the smallest (4.2 ± 0.3 mm). Electrodermal activity (EDA) levels were relatively consistent, with Tissue Retrieval demonstrating the highest mean value (3.5 ± 0.5 microsiemens) and Clip Application the lowest (2.7 ± 0.3 microsiemens). EEG power varied moderately, with Camera Control exhibiting the highest mean power (50.1 ± 3.8 μV²) and Tissue Dissection the lowest (47.3 ± 3.8 μV²) [Table 2].

Table 1: Baseline demographic characteristics of the participants (N=25).

Characteristic	Frequency (%)/Mean ± SD
Age (years)	42.5 ± 5.2
Gender	
Male	18 (72.0%)
Female	7 (28.0%)
Years of Experience	12.8 ± 3.6
Specialty	
General Surgery	16 (64.0%)
Gynecology	6 (24.0%)
Urology	3 (12.0%)
Hand Dominance	
Right	22 (88.0%)
Left	2 (8.0%)
Ambidextrous	1 (4.0%)

Table 2: Comparison of Physiological Parameters Across Surgical Tasks among participants (N=25).

Surgical Task	Mean ± SD			
	HRV (ms)	Pupil Diameter (mm)	EDA (microsiemens)	EEG Power (μV²)
Trocar Placement	75.2 ± 3.5	4.5 ± 0.4	3.2 ± 0.3	45.6 ± 4.2
Tissue Dissection	69.8 ± 3.2	4.2 ± 0.3	2.8 ± 0.2	47.3 ± 3.8
Suturing Practice	72.5 ± 3.0	4.7 ± 0.4	3.0 ± 0.5	48.9 ± 4.1
Knot Tying Exercise	73.6 ± 3.7	4.3 ± 0.5	2.9 ± 0.6	46.7 ± 3.9
Grasping Technique	71.3 ± 3.8	4.4 ± 0.3	3.1 ± 0.4	49.2 ± 4.7
Clip Application	74.1 ± 4.0	4.6 ± 0.4	2.7 ± 0.3	47.8 ± 3.5
Cautery Simulation	76.9 ± 3.6	4.8 ± 0.5	3.3 ± 0.4	46.5 ± 3.9
Tissue Retrieval	77.4 ± 3.9	4.9 ± 0.4	3.5 ± 0.5	48.2 ± 4.3
Camera Control	70.5 ± 3.4	4.1 ± 0.2	2.6 ± 0.4	50.1 ± 3.8
Visualization Exercise	75.8 ± 3.2	4.7 ± 0.3	3.4 ± 0.5	47.6 ± 4.1

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Table 3: Multivariate Regression Models Predicting Cognitive Load.

Predictor Variables	Beta Coefficient	p-value
HRV	0.52	<0.001
Pupil Diameter	-0.28	0.012
EDA	-0.15	0.245
EEG Power	0.67	<0.001
Task Complexity (Control)	-0.2	0.035

Table 4: Task Performance Metrics and Cognitive Load among participants (N=25).

Surgical task	Mean ± SD		
	Completion Time (minutes)	Error Rate (%)	Cognitive Load Score
Trocar Placement	12.3 ± 1.5	8.7 ± 1.2	65.2 ± 3.6
Tissue Dissection	10.5 ± 1.2	5.2 ± 0.9	70.1 ± 2.4
Suturing Practice	11.8 ± 1.4	6.3 ± 1.1	68.9 ± 2.8
Knot Tying Exercise	13.2 ± 1.8	9.1 ± 1.5	67.5 ± 3.0
Grasping Technique	9.7 ± 1.3	4.8 ± 0.7	72.3 ± 2.1
Clip Application	12.5 ± 1.6	7.2 ± 1.0	66.8 ± 2.5
Cautery Simulation	11.0 ± 1.4	5.6 ± 0.8	69.7 ± 2.7
Tissue Retrieval	13.8 ± 1.9	10.2 ± 1.3	64.5 ± 3.2
Camera Control	10.2 ± 1.1	4.3 ± 0.6	73.6 ± 2.5
Visualization Exercise	12.0 ± 1.4	6.8 ± 1.0	68.0 ± 2.6

Table 5: Correlation Matrix between Cognitive Load and Physiological Measures.

Variables	Cognitive Load Score	HRV (ms)	Pupil Diameter (mm)	EDA (microsiemens)	EEG Power (μV²)
	Pearson's coefficient (R)				
HRV	0.72*	1	-0.45	-0.28	0.61*
Pupil	-0.35	-0.48*	1	0.23	-0.42*
EDA	-0.21	-0.29	0.18	1	-0.15
EEG Power	0.61*	0.72*	-0.42*	-0.15	1

*Correlation significant at $p < 0.05$.

The analysis of predictor variables revealed significant associations with cognitive load levels during laparoscopic surgery. Heart rate variability (HRV) showed a positive relationship (β = 0.52, p < 0.001), indicating that higher HRV was associated with increased cognitive load. Conversely, pupil diameter exhibited a negative relationship (β = -0.28, p = 0.012), suggesting that larger pupil diameters were linked to lower cognitive load. Additionally, EEG power demonstrated a strong positive relationship (β = 0.67, p < 0.001) with cognitive load levels. Task complexity, as a control variable, displayed a negative relationship (β = -0.2, p = 0.035) with cognitive load [Table 3].

In our study, among the tasks evaluated, "Grasping Technique" demonstrated the shortest completion time with a mean of 9.7 minutes (±1.3 SD), while "Tissue Retrieval" had the longest completion time with a mean of 13.8 minutes (±1.9 SD). Conversely, "Grasping Technique" also exhibited the lowest error rate at 4.8% (±0.7 SD), indicating a high level of precision during execution. On the other hand, "Tissue Retrieval" recorded the highest error rate at 10.2% (±1.3 SD), suggesting potential challenges encountered during this task. Additionally, cognitive load scores varied across tasks, with "Camera Control" yielding the highest cognitive load score of 73.6 (±2.5 SD), while "Tissue Retrieval" had the lowest score at 64.5 (±3.2 SD) [Table 4].

The correlation analysis revealed significant associations between cognitive load scores and physiological parameters during laparoscopic surgery. Heart rate variability (HRV) showed a strong positive correlation (R = 0.72, p < 0.05), indicating that higher cognitive load was associated with increased HRV. Conversely, pupil diameter demonstrated a moderate negative correlation (R = -0.35, p < 0.05), suggesting that larger pupil diameters were linked to lower cognitive load. EEG power exhibited a robust positive correlation (R = 0.61, p < 0.05) with cognitive load scores. However, electrodermal activity (EDA) did not show a significant correlation (R = -0.21, p > 0.05) with cognitive load scores [Table 5].

DISCUSSION

Our investigation into the physiological correlates of cognitive load in laparoscopic surgery yields insights crucial for understanding surgeon performance and informing training methodologies. The significant positive correlation we observed between heart rate variability (HRV) and cognitive load accords with prior research, affirming HRV's utility as a reliable marker of cognitive load.[10,11] Surgeons experiencing higher cognitive demands tend to exhibit increased HRV, indicative of heightened autonomic nervous system activity. This finding substantiates the role of HRV monitoring as a real-time, non-invasive measure for assessing cognitive load during surgical procedures, echoing the conclusions of similar studies Takada et al., Hinzmann et al., and Jiryis et al.[10-12]

In contrast, our discovery of a negative correlation between pupil diameter and cognitive load departs from traditional expectations but is consistent with recent findings in surgical settings in the studies by Naik et al., Wu et al., Tolvanen et al., and

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Skaramagkas et al.[13-16] Larger pupil diameters were associated with reduced cognitive load, suggesting a potential compensatory mechanism wherein greater visual processing efficiency is required under lower cognitive demands.[13,16] This novel insight underscores the complexity of pupil dynamics and the need for nuanced interpretation within surgical contexts, warranting further investigation.[14]

Our study highlights electroencephalography (EEG) power as a robust predictor of cognitive load, aligning with prior research emphasizing EEG's sensitivity to cognitive engagement levels Shafiei et al., Morales et al., and Dehabadi et al.[17-19] Surgeons experiencing higher cognitive load exhibited elevated EEG power, reflecting increased neural activation associated with heightened cognitive demands.[20] EEG emerges as a promising tool for monitoring cognitive load dynamics during surgery, offering direct insights into brain activity and workload.[21]

Surprisingly, electrodermal activity (EDA) did not exhibit a significant correlation with cognitive load in our study—a departure from previous findings suggesting EDA's potential as a marker of cognitive load.[22,23] This discrepancy underscores the multifaceted nature of physiological responses and the need for further exploration into the factors influencing EDA's relationship with cognitive demand in surgical settings.[24]

Furthermore, our identification of task complexity as a significant predictor of cognitive load underscores the impact of task-specific factors on surgeon workload. Tasks characterized by greater complexity were associated with heightened cognitive load, echoing findings from other studies.[25-28] Surgeons may experience varying cognitive demands depending on the intricacy of the task, emphasizing the importance of tailored training programs and task optimization strategies.[3,7]

CONCLUSION

In summary, our study sheds light on the relationship between physiological parameters and cognitive load during laparoscopic surgery. We found significant associations, with heart rate variability (HRV) and electroencephalography (EEG) power serving as robust indicators of cognitive load, while task complexity emerged as a significant predictor. Pupil diameter displayed a nuanced relationship with cognitive load, while electrodermal activity (EDA) did not show significant correlation. These findings offer insights for refining surgical training and performance assessment protocols, with the potential to enhance patient safety and surgical outcomes. Further research is warranted to validate these findings in larger cohorts and explore additional physiological markers for cognitive load assessment.

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