Laparoscopy and Robotics

Understanding Cognitive Performance During Robot-Assisted Surgery

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OBJECTIVE
To understand cognitive function of an expert surgeon in various surgical scenarios while performing robot-assisted surgery.

MATERIALS AND METHODS
In an Internal Review Board approved study, National Aeronautics and Space Administration-Task Load Index (NASA-TLX) questionnaire with surgical field notes were simultaneously completed. A wireless electroencephalography (EEG) headset was used to monitor brain activity during all procedures. Three key portions were evaluated: lysis of adhesions, extended lymph node dissection, and urethro-vesical anastomosis (UVA). Cognitive metrics extracted were distraction, mental workload, and mental state.

RESULTS
In evaluating lysis of adhesions, mental state (EEG) was associated with better performance (NASA-TLX). Utilizing more mental resources resulted in better performance as self-reported. Outcomes of lysis were highly dependent on cognitive function and decision-making skills. In evaluating extended lymph node dissection, there was a negative correlation between distraction level (EEG) and mental demand, physical demand and effort (NASA-TLX). Similar to lysis of adhesion, utilizing more mental resources resulted in better performance (NASA-TLX). Lastly, with UVA, workload (EEG) negatively correlated with mental and temporal demand and was associated with better performance (NASA-TLX). The EEG recorded workload as seen here was a combination of both cognitive performance (finding solution) and motor workload (execution). Majority of workload was contributed by motor workload of an expert surgeon. During UVA, muscle memory and motor skills of expert are keys to completing the UVA.

CONCLUSION
Cognitive analysis shows that expert surgeons utilized different mental resources based on their need. UROLOGY 86: 751–757, 2015. © 2015 Elsevier Inc.

We are what we repeatedly do. Excellence, then, is not an act, but a habit.
—Aristotle

The art of surgery is performed in a dynamic environment that constantly challenges human performance. Although technical skills are key tenets of surgical performance, factors such as anatomic knowledge and cognitive expertise are required to define a master surgeon. Concerns regarding transferability of skills from simulation-based training have been questioned due to performance anxiety, true interaction in surgical field, and differences in fidelity and mental load.1-3

Poor to virtuoso performance during modern surgery is easily witnessed due to a magnified 3-dimensional view of the surgical field. Surgeons have the opportunity to learn about tool motion with precision and instrument-tissue interaction during robot-assisted surgery, allowing us to evaluate complex dynamics on the operative field.4,5

Cognition-based assessment is critical to graduate from novice to master status during the course of training. Mental workload and engagement are the most common metrics used to evaluate the subject's mental states.6,7 This information is traditionally gathered using self-reported questionnaires and performance-based metrics. Some of these metrics, such as the modified Cooper Harper (MHC) scale,8 are based on averaged workload scales, whereas others such as The National Aeronautics and Space Administration-Task Load Index (NASA-TLX)9 comprise subscales that measure specific mental resources, for example, mental effort, physical effort, etc. The major drawback of these measures is that they cannot be unobtrusively administered during the task, but are assessed at the end of the task, which decreases accuracy and reliability of measurement. Moreover, such methods suffer from subjective biases during self-assessment. New

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advances in brain-computer interfaces have made it possible to monitor individualized cognitive metrics in real time and unobtrusive fashion. The effectiveness of these approaches has already been explored in variety of applications ranging from computer-aided design\textsuperscript{10} to human-robot interaction\textsuperscript{11,12} and sport training.\textsuperscript{13,14}

Cognitive assessment of surgeons has been able to clearly distinguish competent and proficient from expert surgeons, despite inability of traditional tool-based metrics.\textsuperscript{3,15}

Motor skills are proposed to develop in 3 different stages: the cognitive, associative, and autonomous.\textsuperscript{16} Considerable cognitive activity is required at the early stages where the novice is struggling with figuring out the nuances of accomplishing the task. Once the basic skill is acquired, the associative stage begins where he and/or she can direct his attention on the performance rather than the strategy. This cognitive demand will be minimized as the motor skills are mastered and the task can be performed automatically.\textsuperscript{16}

Based on surgical expertise an intuitive, fast, automated decision-making process is observed in a master surgeon based on repetitive, pattern recognition, while expending minimal mental energy expenditure. Meanwhile, a novice surgeon attempts deliberate, logical, and automatic steps. As expertise grows, master surgeons anticipate, preempt, and process technical challenges during unexpected operative scenarios. To our knowledge, this is the first study that focuses on understanding cognitive variability during various surgical scenarios encountered by an expert surgeon in terms of cognitive engagement, mental workload, and mental state.

**MATERIALS AND METHODS**

**Study Design**

This Internal Review Board approved study (I 241913) started enrollment in September 2013. All robot-assisted surgical procedures were performed by an expert surgeon (KG), with more than 1250 surgical procedures and over 6500 console hours experience. All procedures were de-identified and data were collated. Fifty-one procedures (prostatectomy: 21, cystectomy: 26 and reconstruction: 4) were enrolled in the study. NASA-TLX questionnaire together with field notes of the surgical steps were simultaneously documented.

**NASA-Task Load Index Questionnaire**

NASA-TLX is one of the most widely utilized subjective validated instruments for assessment of subjective mental workload.\textsuperscript{9} The NASA-TLX utilizes a 20-point visual analog score and provides an overall index of mental workload as well as the relative contributions of 6 subscales: mental, physical, temporal task demands, effort, frustration, and perceived performance. The psychometric characteristics of the NASA-TLX have been validated and used by the NASA Ames Research Laboratory for subjective evaluation of individual workload during flight simulation, air traffic control, and vigilance tasks. More recently, our group utilized NASA-TLX assessment of workload perception to separate novice, competent, and proficient and expert surgeons.\textsuperscript{15} It should be noted that only for performance assessment in NASA-TLX, perfect performance is associated with a lower numerical value.

**Cognitive Function Assessment**

A 20-channel wireless electroencephalogram (EEG) recording device was used to monitor brain activity using an ABM X 24 neuro-headset (Advanced Brain Monitoring, Inc. Carlsberg, CA) during all surgical procedures. Sensors were placed over frontal, central, parietal, and occipital regions. The cognitive output analysis included cognitive metrics (0.1-1.0) for cognitive engagement, mental workload, and mental state for each 1-second epoch. Signal artifacts such as muscle and eye movements were removed, using filtering and classification techniques.\textsuperscript{6,7} The expert surgeon participated in a baseline prerecording session where he performed tasks and a 3-choice psychomotor vigilance task to compute cognitive indices. During each task participant’s cognitive engagement, mental workload, and mental state were evaluated via wireless EEG recordings.

**Surgical Procedures**

All surgical procedures performed since September 2013 on the da Vinci Surgical System were enrolled in the study. Three key portions, based on level of complexity and different mental challenges while performing prostatectomy and cystectomy, were included in the analysis: Lysis of adhesions (LOA) (n = 20), extended lymph node dissection (eLND) (n = 21), and urethro-vesical anastomosis (UVA) (n = 19). LOA was included to represent a portion of surgery associated with uncertainty (inability to proceed further, possible associated damage to other key organs or vessels, and level of difficulty). eLND requires careful attention around vessel and thoroughness that meets oncological standards. Meanwhile, UVA rather requires repetitive motor-based skills.

**Outcome Measures**

The intended outcome measures included both subjective and cognitive assessment of these 3 complex surgical steps.

**Subjective Metrics.** The subjective metrics recorded were the NASA-TLX questionnaire and the field notes written by the surgeon immediately after completing each individual surgical step. NASA-TLX score is calculated by self-rating on a scale of 1 (low) to 20 (high) for the 6 aforementioned dimensions.

**Cognitive Performance Metrics.** Three main cognitive metrics extracted from the preprocessed signals were: distraction, mental workload, and mental state. The mental state is related to processes involving information gathering, visual scanning, and sustained attention. It includes high-level, low-level engagement, and cognitive state.\textsuperscript{6,7} Distraction measures the level of involvement of cognition of the surgeon while performing the surgical step. Mental workload is correlated with both objective motor performance and loading working memory. Mental state is a discrete index that represents the most probable cognitive state in a given instant (1 second epoch) using numerical values (0.1 = sleep onset, 0.3 = distraction, 0.6 = low engagement, and 0.9 = high engagement). Mental state is represented as combination of high-level engagement and cognitive state.

The surgeon was blinded about the outcomes until the analysis was complete to minimize any cognitive bias. Adequate
effort positively correlated with workload (\(r = 0.44\), \(P = .02\)). Additionally, a negative correlation was found between EEG reported distraction and NASA-TLX parameters: mental demand (\(r = -0.41, P = .02\)), physical demand (\(r = -0.36, P = .04\)), and effort (\(r = -0.41, P = .02\)) (Table 2; Fig. 1).

Extended Lymph Node Dissection (eLND)

Similar to LOA, a negative correlation between mental state and performance was observed (\(r = -0.45, -0.40, P = .01, .02\)). Additionally, a negative correlation was found between the EEG reported distraction level and NASA-TLX parameters: mental demand (\(r = -0.41, P = .02\)), physical demand (\(r = -0.36, P = .04\)), and effort (\(r = -0.41, P = .02\)) (Table 2; Fig. 1).

Urtho-Vesical Anastomosis

Workload (EEG recorded) negatively correlated with subjective assessment of mental demand (\(r = -0.53, P = .02\)), temporal demand (\(r = -0.56, P = .01\)) as well as performance (\(r = -0.46, P = .05\)), and frustration (\(r = -0.46, P = .04\)). Furthermore, the EEG-recorded workload negatively correlated with NASA’s mental demand (\(r = -0.53, P = .02\)), and mental state (EEG) negatively correlated with mental demand (NASA-TLX) (\(r = -0.46, P = .05\)) (Table 3; Fig. 1).

**COMMENT**

Surgery is performed in a dynamic, skill requiring, quick response environment where the limits of timely precise decisions and related action define master performance. Our study constitutes, to the best of our knowledge, the first series of objective cognitive evaluation during surgery. Yurko et al. showed that actual performance in the operating room was more demanding and challenging than simulation training. They utilized NASA-TLX workload questionnaire that provided a valid measure of workload in both the operating room and simulation environment. Our study addressed the real operating room environment with both validated subjective and cognitive evaluation tools. There is paucity of literature focusing on the cognitive evaluation during surgery, especially in different surgical scenarios. The foundations of intraoperative judgment and the surgeon’s mindset will ultimately help define the roadmap toward assessing future surgeons in their capability to handle stressful, difficult, high-risk situations.

Good hand-eye coordination and excellent manual dexterity are not the only factors predicting technical expertise. Scenarios such as “think loud” exercise during wet laboratory have shown that trainees experience difficulty in formulating and verbalizing intraoperative decision-making. In another study, 89% of trainees made errors in decision-making and were unable to complete the procedure. All such studies to date have only attempted to simulate surgical environment and reproduce real-time-like scenarios. The lack of complex tactile feel and surgical performance centered only on visual input make robot-assisted surgery even more intriguing for such a study.

In our study, LOA, like always, presented an unknown surgical challenge addressed by an expert surgeon, with the possibility of failure to proceed with the surgical procedure. Expert surgeons advocate preprocessing which results in quicker and more efficient operational speed.
has been shown that although motor learning allows trainees to achieve the better technical proficiency, this is based on neural efficiency rather than improvement in motor function. This is further supported by functional magnetic resonance imaging studies, which showed that motor practice results in neural activation and adaptation without change in motor performance. Intuition-based pattern recognition helps expert surgeons avoid working memory overload during uncomplicated surgical tasks. Meanwhile based on our findings, uncertainty and ambiguous pattern recognition during LOA lead to utilization of more mental resources, ultimately resulting in perception of better performance based on NASA-TLX. Rapid cognitive assessment and decision-making happens as an iterative immersion back and forth between unconscious and conscious mental processes based on their vast previous experience. Continuous situation awareness and relevance to the surgical scenario is performed real time in the mind of an expert surgeon. Moreover, higher EEG-based workload was perceived as more effort exerted by the expert surgeon.

Any high workload performance that is mentally demanding leaves little capacity to deal with unexpected events, thereby increasing probability of an error. During LOA, surgeons face an unknown challenge that can make or break the procedure utilizing all of their mental resources in a conscious rather than subconscious manner—“second nature.” Cognitive factors have shown to play a greater role in complex unfamiliar situations.

During eLND, the expert surgeon recruited his mental resources with minimal distraction as operative steps were streamlined, with attention toward safe dissection
around blood vessels. This step utilized both cognitive and motor skills, which allowed the surgeon to engage in repetitive, pattern recognition avoiding unforeseen injury. The expert surgeon was cognitively engaged to processing visualization, orientation, rotation, and relative relationship, which has been shown to be important in mechanical reasoning. Wanzel et al examined influence of visual-spatial ability and manual dexterity, and found that efficient hand movements may be determined by the ability to plan and visualize the necessary progression and not by individual dexterous efficient movements. Zhu et al examined EEG activity associated with motor performance during finger tapping. They found that during verbal cognitive stage of acquiring skills, the task narrowed attention and improved the mapping between stimulus and motion. This linkage would be difficult to demonstrate especially in advanced coordinated multiple, motor tasks. Expertise of a surgeon results from a complex process of learning and practicing with development of networks of implicit knowledge, pattern recognition, and motor memory.

UVA has been standardized and visual-spatial processing has evolved the skill level of automation. With an experience of over 1500 robot-assisted radical prostatectomies over a decade, experience has evolved into motor planning reflecting pattern recognition and minimal use of working memory to accomplish UVA. The EEG-recorded workload as seen here is a combination of both cognitive (finding solution) and motor workload (execution). Since there is a negative correlation between mental demand (NASA-TLX) and mental state (EEG measures), the majority of workload measured during UVA was contributed by motor workload of the surgeon (processing the next key needle maneuver) and executing the motion (motor execution). This illustrates that during UVA, muscle memory and motor skills (already acquired by expert) are keys in the effortless continuum of motion to completing the UVA. It is noted here that the increased workload was associated with lower self-rated frustration, which was mostly attributed to the confidence and experience of the surgeon. Spatial ability helps processing visualization, orientation, rotation, and relative relationship, which has been shown to be important in mechanical reasoning.

### Table 2. Correlation between cognitive function (EEG) and NASA-TLX during eLND

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mental Demand</th>
<th>Physical Demand</th>
<th>Temporal Demand</th>
<th>Performance</th>
<th>Effort</th>
<th>Frustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distraction</td>
<td>-0.41</td>
<td>-0.36</td>
<td>-0.10</td>
<td>0.03</td>
<td>-0.41</td>
<td>0.04</td>
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<td>Mental state</td>
<td></td>
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<td></td>
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<tr>
<td>High engagement</td>
<td>0.28</td>
<td>0.08</td>
<td>-0.14</td>
<td>-0.45</td>
<td>0.22</td>
<td>-0.23</td>
</tr>
<tr>
<td>Cognitive state</td>
<td>0.22</td>
<td>0.11</td>
<td>-0.13</td>
<td>-0.40</td>
<td>0.19</td>
<td>-0.21</td>
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<tr>
<td>Workload</td>
<td>-0.03</td>
<td>0.07</td>
<td>0.02</td>
<td>0.02</td>
<td>-0.03</td>
<td>0.09</td>
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<tr>
<td><strong>P-value correlation for eLND</strong></td>
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</tr>
<tr>
<td>Distraction</td>
<td>0.02</td>
<td>0.04</td>
<td>0.60</td>
<td>0.88</td>
<td>0.02</td>
<td>0.85</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High engagement</td>
<td>0.12</td>
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<td>0.44</td>
<td>0.01</td>
<td>0.22</td>
<td>0.21</td>
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<tr>
<td>Cognitive state</td>
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<td>0.54</td>
<td>0.47</td>
<td>0.02</td>
<td>0.29</td>
<td>0.24</td>
</tr>
<tr>
<td>Workload</td>
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<td>0.72</td>
<td>0.89</td>
<td>0.91</td>
<td>0.88</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Values in bold indicate significant correlations and corresponding P-value.

### Table 3. Correlation between cognitive function (EEG) and NASA-TLX during Urethro-Vesical Anastomosis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mental Demand</th>
<th>Physical Demand</th>
<th>Temporal Demand</th>
<th>Performance</th>
<th>Effort</th>
<th>Frustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distraction</td>
<td>0.07</td>
<td>-0.09</td>
<td>0.07</td>
<td>-0.09</td>
<td>-0.18</td>
<td>-0.01</td>
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<tr>
<td>Mental state</td>
<td></td>
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</tr>
<tr>
<td>High engagement</td>
<td>-0.34</td>
<td>-0.25</td>
<td>-0.24</td>
<td>-0.19</td>
<td>-0.28</td>
<td>-0.28</td>
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<tr>
<td>Cognitive state</td>
<td>-0.46</td>
<td>-0.37</td>
<td>-0.40</td>
<td>-0.38</td>
<td>-0.44</td>
<td>-0.44</td>
</tr>
<tr>
<td>Workload</td>
<td>-0.53</td>
<td>-0.45</td>
<td>-0.56</td>
<td>-0.46</td>
<td>-0.41</td>
<td>-0.48</td>
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<tr>
<td><strong>P-value correlation for UVA</strong></td>
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<td></td>
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<tr>
<td>Distraction</td>
<td>0.78</td>
<td>0.73</td>
<td>0.79</td>
<td>0.73</td>
<td>0.47</td>
<td>0.98</td>
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<tr>
<td>Mental state</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High engagement</td>
<td>0.16</td>
<td>0.31</td>
<td>0.31</td>
<td>0.44</td>
<td>0.40</td>
<td>0.24</td>
</tr>
<tr>
<td>Cognitive state</td>
<td>0.05</td>
<td>0.12</td>
<td>0.09</td>
<td>0.11</td>
<td>0.13</td>
<td>0.06</td>
</tr>
<tr>
<td>Workload</td>
<td>0.02</td>
<td>0.06</td>
<td><strong>0.01</strong></td>
<td><strong>0.05</strong></td>
<td>0.08</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Values in bold indicate significant correlations and corresponding P-value.
performance.” Michigan Bariatric Surgery Collaborative used data from 40 hospitals (63 surgeons) and evaluated 5 domains of surgical skills from surgical videos provided by participating surgeons.29 This was collaborated with prospective collection of complication outcomes. This study was able to identify surgical variability and showed that surgical performance was linked to outcomes. Surgical skill assessment will definitely move forward with studies like ours; evolution of such methods may play a role in trainee selection, completion of training, future privileging, and credentialing. These findings may also help assess and monitor progress in surgeons in need of remediation. It takes surgeons and surgical education experts out of their comfort zone and may be challenging to comprehend, but the potential preclinical (surgical interest group counseling), clinical, and its role in assessment may completely change how we approach surgical training. We might be able to significantly reduce 10,000 hours of deliberate practice to time efficient EEG biofeedback training, when goal-directed and process-oriented learning can change cortical dynamics.13,30

Despite the uniqueness of this study, it has several limitations. We used a wireless headgear that brought with it technical limitations in terms of time to accurately position and calibrate the headgear. The equipment is wireless and light, but intrusive especially during lengthy procedures. We did reduce and optimize our set-up time once few cases were recorded. The headgear caused some discomfort that diminished with time. Also, the transmission is gel-based which may loosen during prolonged recordings and affect the quality of the signal. Adequate signal transduction during our study was ensured before each procedure. NASA-TLX is a validated workload assessment tool; it still measures subjective opinion of one’s cognitive demand after each surgical step. This may be associated with judgment and recall biases. However, we believe it can still reflect a true representation of the workload as all questionnaires were completed immediately after each surgical step. We were not able to account for other factors (operative length, time of surgery, and level of fatigue) that may alter the mental load during the study. This study only evaluated one expert surgeon’s cognitive performance; similar results from surgeries performed by different surgeons in future would increase the validity of this work.

In summary, different surgical scenarios were paralleled by variability in cognitive performance, from an unknown challenge where the surgeon transitions from an automated mode to an effortful thought out surgical step (LOA), to a process involving cognitive engagement and technical skills while performing (eLND), and finally a repetitive motor skill (UVA). The expert surgeon should be able to go from using minimal cognitive resources (second nature) to consciously processing every move to solve an unusual, uneventful situation safely for the patient on the operating table.

**CONCLUSION**

Cognitive analysis shows that the expert surgeons utilize different mental resources based on their need. It is important to understand the depth and mechanism of such cognitive findings, so that we can safely counsel a trainee regarding their surgical capabilities and help them reach and maintain their expert potential.

**References**


