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Surgeons' display reduced mental effort and workload while performing robotically assisted surgical tasks, when compared to conventional laparoscopy

Running Head: Benefits of robotic surgery

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Abstract

Background. Research has demonstrated the benefits of robotic surgery for the patient; however, research examining the benefits of robotic technology for the surgeon is limited. This study aimed to adopt validated measures of workload, mental effort, and gaze control to assess the benefits of robotic surgery for the surgeon. We predicted that the performance of surgical training tasks on a surgical robot would require lower investments of workload and mental effort, and would be accompanied by greater gaze control and better performance, when compared to conventional laparoscopy.

Methods. Thirty-two surgeons performed two trials on a ball pick-and-drop task and a rope threading task on both robotic and laparoscopic systems. Measures of workload (The Surgery Task Load Index [SURG-TLX]), mental effort (subjective: Rating Scale for Mental Effort [RSME] and objective: standard deviation of beat-to-beat intervals [SDNN]), gaze control (using a mobile eye movement recorder), and task performance (completion time and number of errors) were recorded.

Results. As expected, surgeons performed both tasks more quickly and accurately (with fewer errors) on the robotic system. Self-reported measures of workload and mental effort were significantly lower on the robotic system compared to the laparoscopic system. Similarly, an objective cardiovascular measure of mental effort revealed lower investment of mental effort when using the robotic platform relative to the laparoscopic platform. Gaze control distinguished the robotic from the laparoscopic systems, but not in the predicted fashion, with the robotic system associated with poorer gaze control.

Conclusions. The findings highlight the benefits of robotic technology for surgical operators. Specifically, they suggest that tasks can be performed more proficiently, at a lower workload, and with the investment of less mental effort and gaze control, potentially allowing surgeons greater cognitive resources for dealing with other demands such as communication, decision-making, or periods of increased complexity in the operating room.

Key words: Robotic surgery; laparoscopic surgery; workload; mental effort; gaze control.

Surgeons' display reduced mental effort and workload while performing robotically assisted surgical tasks, when compared to conventional laparoscopy.

Introduction

Compared to traditional laparoscopy, robotic surgery offers a number of important benefits to the patient including smaller incisions, reduced blood loss and post-operative pain, and reduced durations of in-patient care [1]. A number of clinical studies have confirmed the viability and safety of robotics, and the benefits for patient outcome [2-3]. Laparoscopy provides unique challenges for the surgeon; the reduced dexterity of the elongated tools, the limited freedom of movement within the abdomen, and the 2-dimensional field of view, place high physical and mental demands upon the surgeon. Robotic systems (e.g., the da Vinci Si; Intuitive Surgical Ltd., Sunnyvale, California), are proposed to overcome some of these challenges for the surgeon; the high resolution 3-dimensional field of view, improved dexterity, and tremor filtering are proposed to benefit the surgeon by reducing the mental and physical demands of procedures. However, research examining these claims is limited. The aim of this study was to test these propositions, using validated and scientifically rigorous measures of workload and mental effort.

A number of recent studies have examined the workload associated with performing various surgical tasks on robotic and laparoscopic systems [4-7]. For example, Panait and colleagues found that surgeons reported lower workloads when completing circle cutting and intracorporeal suturing tasks on a robotic platform compared to a laparoscopic platform [8]. However, a limitation of this research is that workload was assessed using a measure borrowed from human factors research (National Aeronautics and Space Administration Task Load Index; NASA-TLX) [9], rather than a validated multi-dimensional measure developed specifically for the surgical environment (Surgery Task Load Index; SURG-TLX) [10]. Furthermore, in the majority of these studies only total workload was reported and no attempts were made to identify the sub-constructs of workload that are most influenced by robotic technology (mental demand, physical demand, temporal demand etc.).

Additionally, much of the recent workload research has predominately focused on measures of physical effort expenditure using techniques such as electromyography [4]. For instance, Lee and colleagues showed that surgeons exhibited less activation in the biceps and flexor carpi ulnaris muscles of the arms when completing tasks on a robotic rather than laparoscopic system [5]. Indeed, in comparison to physical effort, the investment of mental effort has been largely ignored despite research in the fields of aviation and ergonomics suggesting that mental overload can cause poor task performance, particularly if a concurrent task also needs to be completed [11]. This is an important consideration given that surgeons are often required to multi-task and effectively deal with many noises and distractions in the operating room [12]. Crucially, mental effort can be easily assessed both subjectively and objectively using well established and validated measures [13].

The majority of studies examining workload have investigated how robotic and laparoscopic techniques influence surgical task performance [14]. For example, Lee and colleagues showed that surgeons had higher global performance scores, reflecting reduced performance times and error rates, when utilizing a robotic system compared to conventional laparoscopy [5]. Recent research has identified that proficiency-related differences in laparoscopy performance can be indexed by the gaze control of the surgeon. This research has identified that proficient surgical performance in laparoscopic tasks is associated with more sustained fixations to the target to be manipulated rather than the tool (a 'target-locking' rather than 'switching' gaze strategy) [15-19]. Thus, eye tracking technology may provide an objective method by which to assess performance-related differences in robotic and conventional laparoscopy. A surgeon performing a task on a robotic system may display more ‘expert-like’ gaze control, with the improved dexterity afforded by the robot resulting in greater target-locking and less switching between the target and tool.

The aim of this study was to compare the workload, mental effort, performance, and gaze control of experienced surgeons completing surgical tasks using both robotic and laparoscopic systems. The proposed benefits of the robotic system (3-dimensional field of view, improved dexterity etc.) were predicted to result in the surgeons reporting lower workload and mental effort when performing a surgical training task on the robotic system compared to the laparoscopic system. Moreover, these benefits were hypothesized to lead to the surgeons displaying more ‘expert-like’ gaze control and completing the tasks more quickly and accurately (fewer errors) on the robotic system.

Materials and Methods

Participants

Thirty-two qualified and trainee surgeons (27 Male, 5 Female; Mean age = 39.91 years, *SD* = 8.96; 24 qualified and 8 trainee surgeons) volunteered to take part in the study. On average, the surgeons had relatively limited robotic experience (Mean number of procedures = 7.56, *SD* = 28.83) and fairly extensive laparoscopic experience (Mean number of procedures = 384.03, *SD* = 906.11). This information was gathered via a brief demographic questionnaire. All surgeons were right-hand dominant. Institutional ethical approval was obtained before commencement of the study, and all surgeons provided written informed consent prior to their individual testing session. Importantly, all surgeons were naïve to the purpose and hypotheses of the study prior to participation.

Surgical Systems and Tasks

A da Vinci Si robotic system (Intuitive Surgical Ltd., Sunnyvale, California) was used in the present study. This system consisted of two primary components: the surgeons control and viewing console, and a moveable cart with three articulated robot arms. The surgeon was seated in front of the console, looking at an enlarged three-dimensional image of the task while manipulating handles that moved the robotic arms. Laparoscopic instruments were attached to two of these arms while the third arm carried an endoscope. Importantly, the surgeons did not need to manipulate the robot arm with the endoscope as it was ensured that each task was in full view. A 3-Dmed (3-Dmed, Franklin, OH) standard minimally invasive training system with a joystick SimScope (a manoeuvrable webcam) was also employed. The scene inside the training box was viewed on a monitor (via a webcam) and surgical tools were inserted through a port on the box allowing objects to be moved inside the box. Each task was in full view to ensure that the surgeons did not need to manipulate the joystick SimScope at any stage.

The surgeons completed two tasks. First, the surgeons performed a ball pick-and-drop task that required the surgeons to move six foam balls from stems of varying heights into a cup, using a single tool (with their dominant hand). The balls had to be grasped and dropped into the cup individually and in a pre-specified order. The surgeons were asked to complete this task as quickly and as accurately (no dropped balls) as they could [19]. Importantly, previous research has shown that this task can be used to improve laparoscopic skills. Additionally, the surgeons performed a rope threading task that required the surgeons to pass a rope through a succession of seven pre-specified metal hoops to create a P configuration, using two tools (with their dominant and non-dominant hands). The surgeons were asked to complete this task as quickly as possible. Crucially, previous research has demonstrated that this task is sensitive to expertise and system differences [20].

Measures

Workload

Surgical workload was assessed using a recently developed and validated multi-dimensional measure called the SURG-TLX [10]. This measure assesses six workload dimensions including mental demands, physical demands, temporal demands, task complexity, situational stress, and distractions. The SURG-TLX requires a two-part evaluation to be completed. In the first part, the surgeons were asked to make 15-paired comparisons so that weights of the six dimensions could be calculated. The dimension with the highest weight was then deemed the most important contributing factor for the perceived workload (scores ranged from 0 to 5). The second part required the surgeons to complete six bipolar scales reflecting the separate dimensions on a 20-point Likert scale anchored between very low and very high. A workload score for each dimension was then calculated by determining the product of these two numbers. For example, a weight score of 4 and a rating of 15 equated to a workload score of 60 (scores ranged from 0 to 100). Finally, a total workload score was then determined by aggregating the scores from the six dimensions (scores range from 0 to 600).

Mental Effort

Self-reported mental effort was assessed using the Rating Scale for Mental Effort (RSME) [21]. The RSME consists of a vertical axis scale with a range of 0-150, with nine descriptive indicators ranging from 3 (absolutely no effort) to 114 (extreme effort). The surgeons were asked to indicate on the scale how much mental effort they invested during the task they had just finished. This scale has been shown to have acceptable reliability in various laboratory settings (r = .88) [21].

Objective mental effort was assessed using a time domain index of heart rate variability derived from the standard deviation of beat-to-beat intervals (SDNN). The SDNN is a correlate of the 0.04 - 0.15 Hz frequency domain based spectral power band (r = .84) [22], which includes the 0.07 - 0.14 Hz component that is sensitive to variations in mental effort in laboratory settings (higher SDNN reflects less mental effort) [23]. The beat-to-beat intervals were calculated and recorded automatically by the heart rate monitor (Polar S810i). The raw beat-to-beat interval data was then filtered using the automatic algorithm in the Polar Precision Performance SW analysis software, set at moderate filtering level. The filtered data was then analyzed with Kubios HRV Analysis Software (Biosignal Analysis and Medical Imaging Group, University of Eastern Finland) [24]. The software calculated SDNN (in ms) during each task on each system for 20 surgeons. Unfortunately, due to poor signal quality, heart rate variability data from 12 surgeons could not be analyzed.

Task Performance

Performance on the ball pick-and-drop task was averaged across the two trials and assessed in terms of both the time taken to complete each trial and the number of errors made during each trial (the number of balls dropped and/or knocked off) [19]. Furthermore, performance the rope threading task was averaged across the two trials and measured by the time taken to complete the task (form the P configuration) [20].

Gaze Control

Eye movements were recorded using a saccadometer (Ober Consulting, Poland). This device sat on the bridge of the surgeons' nose and was kept in place by an elastic strap around their head. The device was attached to a recording unit that was connected to a laptop (Dell Inspiron1400) installed with Jazz Recorder Software (Ober Consulting, Poland). The device continuously recorded eye position by changes in binocular infra-red scleral reflectance at a sampling rate of 1 kHz [25]. Once the device was fitted, a calibration was performed during which the surgeons had to look at high contrast red dots projected onto a blank wall at three different angles (10° left, 0°, or 10° right of center) by low-powered lasers. The continuous record function of the Jazz Recorder Software was then used to record eye positions throughout the tasks.

The eye position data was then exported into a text file using Jazz Manager Software (Ober Consulting, Poland) and analyzed using a MatLab (MathWorks, USA) script. This script converted the eye position data into degrees of visual angle using a calibration factor derived from the calibration data. In the present study, a fixation was defined as when eye position remained on a location within 3° of visual angle for a minimum of 100 ms [26]. Thus, the script was written to detect the number of times that visual angle changed by 3° or more and to count the number of visual angle recordings between each change in visual angle. If visual angle remained within 3° of visual angle for 1000 visual angle recordings or more (100 ms or longer), this was recorded as a fixation. This information was then used to calculate the number of fixations per minute (fixation rate) using the formula: [(number of fixations / completion time) x 60000], whereby a lower fixation rate is a proxy measure of greater target-locking and less switching.

Procedure

After arriving at the laboratory, the surgeons read an information sheet before providing written informed consent and completing a brief demographic questionnaire. The surgeons were then fitted with the heart rate monitor (Polar S810i, Polar Electro Oy, Finland) that was located beneath their clothing to allow complete freedom of movement. In addition, the surgeons were also fitted with the saccadometer (Ober Consulting, Poland) to assess gaze control. Next, the surgeons received instructions regarding the tasks, and performed two trials on each task (in a counterbalanced order). Prior to performing each task on each system, the surgeons were shown how to operate the system and were given one minute to familiarize themselves with the system. Performance, heart rate, and gaze data were recorded continuously throughout both trials on each task on each system. Moreover, self-report measures of mental effort and workload were completed after each task on each system. Finally, at the end of the study, the heart rate monitor and saccadometer were removed, and surgeons were debriefed and thanked for their participation.

Statistical Analyses

A series of dependent *t*-tests were conducted on the workload (SURG-TLX), mental effort (RSME and SDNN), task performance (completion time and number of errors), and gaze control (fixation rate) data. Effect sizes were calculated using Cohen's *d*.

Results

Ball Pick-and-Drop Task

Workload

The dependent *t*-test on the SURG-TLX data revealed that the surgeons reported less total workload when completing the task on the robotic system compared to the laparoscopic system ($t(31) = -3.48$, $p = .002$, $d = 1.25$). A series of dependent *t*-tests indicated that this was mainly due to the surgeons experiencing less stress on the robotic system than the laparoscopic system ($t(31) = -2.20$, $p = .036$, $d = 0.79$). Although the other dimensions of workload (mental demands, physical demands, temporal demands, task complexity, and distractions) also suggested benefits for the robotic system over the laparoscopic system, none of these differences were statistically significant (all *ps* > .070). The workload data are presented in Table 1.

Mental Effort

The dependent *t*-test on the RSME data revealed that the surgeons reported that the task required less mental effort on the robotic system than the laparoscopic system ($t(31) = -3.99$, $p < .001$, $d = 1.43$). Furthermore, the dependent *t*-test on the SDNN data indicated no significant differences between the systems, although the difference did equate to a small to medium effect size ($t(19) = 0.89$, $p = .387$, $d = 0.41$). Indeed, the data was in the predicted direction, the surgeons exhibited higher SDNN (reflecting lower mental effort) when performing the task on the robotic system compared to the laparoscopic system. The mental effort data are presented in Table 1.

Task Performance

The dependent *t*-test on the completion time data revealed no significant difference between the systems ($t(31) = 0.71$, $p = .482$, $d = 0.26$). However, the dependent *t*-test on the number of errors data revealed a significant difference between the systems ($t(31) = -3.85$, $p = .001$, $d = 1.38$). The surgeons made fewer errors on the robotic system than the laparoscopic system. The performance data are presented in Table 1.[1]

Gaze Control

The dependent *t*-test on the fixation rate data revealed a significant difference between the systems ($t(31) = 10.57$, $p < .001$, $d = 3.80$). The surgeons displayed a higher fixation rate (less target-locking and more switching) when performing the task on the robotic system than the laparoscopic system. The gaze data are presented in Table 1.

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[1] While there were no significant differences between the qualified and trainee surgeons in terms of number of errors, the qualified surgeons completed the task quicker on the laparoscopic system. Furthermore, although number of previous laparoscopic procedures was not related to performance on this task on either system, number of prior robotic procedures was related to performance on this task on the robotic system.

Insert Table 1 near here

Rope Threading Task

Workload

The dependent *t*-test on the SURG-TLX data revealed that the surgeons reported less total workload when completing the task on the robotic system compared to the laparoscopic system ($t(31) = -3.58$, $p = .001$, $d = 1.29$). A series of dependent *t*-tests indicated that this was mainly due to the surgeons finding the task less physically demanding ($t(31) = -4.19$, $p < .001$, $d = 1.51$) and complex ($t(31) = -2.09$, $p = .045$, $d = 0.75$) on the robotic system. While the other dimensions of workload (mental demands, physical demands, temporal demands, situational stress, and distractions) also implied advantages for the robotic system over the laparoscopic system, none of these differences were statistically significant (all *ps* > .209). The workload data are presented in Table 2.

Mental Effort

The dependent *t*-test on the RSME data revealed that the surgeons reported that the task required less mental effort on the robotic system than the laparoscopic system ($t(31) = -4.49$, $p < .001$, $d = 1.61$). Furthermore, the dependent *t*-test on the SDNN data indicated no significant differences between the systems, although the difference did equate to a small to medium effect size ($t(19) = 0.98$, $p = .342$, $d = 0.45$). Indeed, the data was in the predicted direction, the surgeons exhibited higher SDNN (reflecting lower mental effort) when performing the task on the robotic system compared to the laparoscopic system. The mental effort data are presented in Table 2.

Task Performance

The dependent *t*-test on the completion time data indicated a significant difference between the systems ($t(31) = -4.15$, $p < .001$, $d = 1.49$). The surgeons completed the task more quickly on the robotic system than the laparoscopic system. The performance data are presented in Table 2.[2]

Gaze Control

The dependent *t*-test on the fixation rate data revealed a significant difference between the systems ($t(31) = 8.64$, $p < .001$, $d = 3.10$). The surgeons displayed a higher fixation rate (less target-locking and more switching) when performing the task on the robotic system than the laparoscopic system. The gaze data are presented in Table 2.

Insert Table 2 near here

Discussion

In addition to the benefits they provide to the patient (reduced blood loss and post-operative pain etc.) [1], robotic systems offer a high resolution 3-dimensional field of view and improved dexterity which are suggested to benefit the surgeon by reducing the physical and mental demands of a procedure. Indeed, research has shown that these features result in tasks being completed more quickly, accurately, and at a lower workload using a robotic rather than laparoscopic system [4-8, 14]. However, the research examining these contentions had some notable limitations. The current study adopted validated measures of workload, mental effort, and gaze control to examine the benefits of robotic surgery for the surgeon.

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[2] While there was no significant difference in the time it took the qualified and trainee surgeons to complete this task on the robotic system, the qualified surgeons completed the task quicker on the laparoscopic system. Moreover, although number of previous laparoscopic procedures was not related to performance on this task on either system, number of prior robotic procedures was related to performance on this task on the robotic system.

As predicted, the surgeons reported experiencing less total workload when performing the tasks on the robotic system compared to the laparoscopic system. This finding supports previous research that has found similar reductions in workload with robotic devices [4-8]. However, previous research used a general workload measure adopted from human factors research (NASA-TLX) [9], rather than a recently developed and validated surgery-specific index of workload like the measure employed in the present study (SURG-TLX) [10]. Moreover, most of this research only reported total workload and did not outline the specific sources of workload most influenced by robotic technology. Indeed, the results of the current study are consistent with the limited research to date and suggest that the lower workload was primarily due to the surgeons finding the tasks less stressful [27-29], physically demanding [4], and complex, on the robotic system. Collectively, these results suggest that by utilizing robotic technology surgeons can operate at lower workloads, an important benefit given the strong links between work overload and performance errors, stress-related disorders, and burnout [11, 30].

After both tasks, as hypothesized, the surgeons noted that they invested less mental effort on the robotic platform relative to the laparoscopic platform. The direction of the objective heart rate variability data also supported this contention, with the surgeons exhibiting higher SDNN (reflecting lower mental effort) when using the robotic platform. However, despite equating to a small to medium effect size, this difference was not statistically significant, possibly owing to a reduction in statistical power caused by the loss of 12 surgeons' data due to equipment problems. Regardless, taken together, the findings suggest that when using robotic technology, surgeons working memory resources may be less stretched, leaving more cognitive resources to help them deal with other demands such as communication, decision-making, or periods of increased complexity in the operating room. These findings may have important implications, as the ability to multi-task and effectively cope with the many noises and distractions in the operating room is regarded as a key skill for surgeons to perform proficiently [12, 31].

The surgeons performed both tasks better on the robotic system than the laparoscopic system. In line with our predictions and previous research [5, 14], the surgeons made fewer errors on the ball pick-and-drop task and completed the rope threading task more quickly using the robotic platform. However, in contrast to our hypothesis, the surgeons displayed higher fixation rates (reflecting less target-locking and more switching between the targets and tools) when performing the tasks on the robotic device. Thus, based on the findings of previous research in laparoscopy [15-19], the surgeons' superior performance on the robotic system was accompanied by less effective 'novice-like' gaze control. While unexpected, this finding is likely due to the surgical tasks being considerably easier on the robotic system and therefore requiring less goal-directed visual attentional control. That is, the high resolution 3-dimensional field of view and improved dexterity may have reduced the visuomotor demands of the tasks, rendering a target-locking gaze strategy unnecessary. Alternatively, the higher fixation rate may just be a reflection of the robotic systems more complex visual display. These explanations should be explored in future research using more accurate and sensitive gaze registration systems that allow for a more detailed coding and analysis of eye movements. Nevertheless, gaze control measures distinguished the robotic system from the laparoscopy system, further highlighting their potential as an objective measurement device in surgical environments [32].

To conclude, the results of the present study demonstrate some of the benefits robotic technology can have for surgical operators. Specifically, the findings suggest that surgical tasks can be performed more proficiently and at a lower workload with a robotic system, possibly reducing surgeon's risk of overload-induced performance errors, stress-related disorders, and burnout. Furthermore, the findings show that surgical tasks can be completed with the investment of less mental effort using a robotic device, potentially allowing surgeons greater cognitive resources for dealing with other demands such as communication, decision-making, or periods of increased complexity in the operating room. However, further research is required to examine the role of gaze control in robotic procedures.

Disclosures

This research was funded by Intuitive Surgical Ltd. through their, 'Surgical Clinical Robotics Research Grant' scheme. However, Intuitive Surgical Ltd. had no involvement in the design and execution of the research, nor in the analysis or interpretation of the data presented. Therefore, Mr Lee Moore, Ms Elizabeth Waine, Dr Mark Wilson, Mr John McGrath, Dr Rich Masters and Dr Samuel Vine have no conflicts of interest or financial ties to disclose.

References

[1] Payne TN, Dauterive FR (2008) A comparison of total laparoscopic hysterectomy to robotically assisted hysterectomy: Surgical outcomes in a community practice *J Minim Invasive Gynecol* 15:286-291.

[2] Trinh Q, Sammon J, Sun M, Ravi P, Ghani KR, Bianchi M, Jeong W, Shariat SF, Hansen J, Schmitges J, Jeldres C, Rogers CG, Peabody JO, Montorsi F, Menon M, Karakiewick PI (2012) Preoperative outcomes of robot-assisted radical prostatectomy: Results from the nationwide inpatient sample *Eur Urol* 61:679-685.

[3] Hakimi AA, Blitstein J, Feder M, Shaprio E, Ghavamian R (2009) Direct comparison of surgical and functional outcomes of robotic-assisted versus pure laparoscopic radical prostatectomy: Single-surgeon experience *Urology* 73:119-123.

[4] Hubert N, Gilles M, Desbrosses K, Meyer JP, Felblinger J, Hubert J (2013) Ergonomic assessment of the surgeon's physical workload during standard and robotic assisted laparoscopic procedures *Int J Med Robotics Comput Assist Surg* 9:142-147.

[5] Lee GI, Lee MR, Clanton T, Sutton E, Park AE, Marohn MR (2014) Comparative assessment of physical and cognitive ergonomics associated with robotic and traditional laparoscopic surgeries *Surg Endosc* 28:456-465.

[6] Stefanidis D, Hope WW, Scott DJ (2011) Robotic suturing on the FLS model possesses construct validity, is less physically demanding, and is favoured by more surgeons compared with laparoscopy *Surg Endosc* 25:2141-2146.

[7] Stefanidis D, Wang F, Korndorffer Jr JR, Dunne JB, Scott DJ (2010) Robotic assistance improves intracorporeal suturing performance and safety in the operating room while decreasing operator workload *Surg Endosc* 24:377-382.

[8] Panait L, Shetty S, Shewokis PA, Sanchez JA (2014) Do laparoscopic skills transfer to robotic surgery? *J Surg Res* 187:53-58.

[9] Hart S, Staveland L (1988) Development of Nasa-Tlx (Task Load Index): Results of empirical and theoretical research *Hum Ment Workload* 1:139-183.

[10] Wilson MR, Poolton JM, Malhotra N, Ngo K, Bright E, Masters RSW (2011) Development and validation of a surgical workload measure: The Surgery Task Load Index (SURG-TLX) *World J Surg* 35:1961-1969.

[11] Hilburn B, Jorna PGAM (2001) Workload and air traffic control. In: Hancock PA, Desmond PA (Eds.) Stress, workload and fatigue, New Jersey, Lawrence Erlbaum Associates, pp. 384-394.

[12] Healey AN, Sevdalis N, Vincent CA (2006) Measuring intraoperative interference from distraction and interruption observed in the operating theatre *Ergonomics* 49:589-604.

[13] Wilson MW, Smith NC, Holmes PS (2007) The role of effort in mediating the anxiety performance relationship: Testing the conflicting predictions of the processing efficiency theory and the conscious processing hypothesis *Brit J Psychol* 98:411-428.

[14]. Hubens G, Coveliers H, Balliu L, Ruppert M, Vaneerdeweg W (2003) A performance study comparing manual and robotically assisted laparoscopic surgery using the da Vinci system *Surg Endosc* 17:1595-1599.

[15] Wilson M, McGrath J, Vine S, Brewer J, Defriend D, Masters R (2010) Psychomotor control in a virtual laparoscopic surgery training environment: Gaze control parameters differentiate novices from experts *Surg Endosc* 24:2458-2464.

[16] Wilson MR, McGrath JS, Vine SJ, Brewer J, Defriend D, Masters RSW (2011) Perceptual impairment and psychomotor control in virtual laparoscopic surgery *Surg Endosc* 25:2268-2274.

[17] Wilson MR, Vine SJ, Bright E, Masters RSW, Defriend D, McGrath JS (2011) Gaze training enhances laparoscopic technical skill acquisition and multi-tasking performance: A randomized, controlled study *Surg Endosc* 25:3731-3739.

[18] Vine SJ, Masters RSW, McGrath JS, Bright E, Wilson MR (2012) Cheating experience: Guiding novices to adopt the gaze strategies of experts expedites the learning of technical laparoscopic skills *Surgery* 152:32-40.

[19] Vine SJ, Chaytor RJ, McGrath JS, Masters RSW, Wilson MR (2013) Gaze training improves the retention and transfer of laparoscopic technical skills in novices *Surg Endosc* 27:3205-3213.

[20] Yohannes P, Rotariu P, Pinto P, Smith AD, Lee BR (2002) Comparison of robotic versus laparoscopic skills: Is there a difference in the learning curve? *Adult Urol* 60:39-45.

[21] Zijlstra FRH (1993) Efficiency in work behaviour: A design approach for modern tools, Delft, Delft University Press.

[22] Carrasco S, Gaitan MJ, Gonzalez R, Yanez O (2001) Correlation among poincare plot indexes and time and frequency domain measures of heart rate variability *J Med Eng Technol* 25:240-248.

[23] Mulder G, Mulder LJM, Meijman TF, Veldman JBP, Van Roon AM (2000) A psychophysiological approach to working conditions. In: Backs RW, Boucsein W (Eds.) Engineering psychophysiology: Issues and applications, Mahwah, NJ, Lawrence Erlbaum Associates, pp. 139-159.

[24] Tarvainen MP, Niskanen JP, Lipponen JA, Ranta-Aho PO, Karjalainen PA (2014) Kubios HRV – Heart rate variability analysis software *Comput Meth Prog Bio* 113:210-220.

[25] Ober JK, Przedpelska-Ober E, Gryncewicz W, Dylak J, Carpenter RHS, Ober JJ (2003) Hand-held system for ambulatory measurement of saccadic durations of neurological patients. In: Gadja J (Ed.) Modelling and Measurement in Medicine Komitet Biocybernityki i Inzynneierii Biomedycznej, PAN, Warsaw, pp. 187-198.

[26] Vickers JN (2011) Mind over muscle: The role of gaze control, spatial cognition, and the quiet eye in motor expertise *Cogn Process* 12:219-222.

[27] Klein MI, Warm JS, Riley MA, Matthews G, Doarn C, Donovan JF, Gaitonde K (2012) Mental workload and stress perceived by novice operators in the laparoscopic and robotic minimally invasive surgical interfaces *J Endouro* 26:1089-1094.

[28] Klein MI, Mouraviev V, Craig C, Salamone L, Plerhoples TA, Wren SM, Gaitonde K (2014) Mental stress experienced by first-year residents and expert surgeons with robotic and laparoscopic surgery interfaces *J Robotic Surg* 8:149-155.

[29] Van der Schatte Olivier RH, Van't Hullenaar CDP, Ruurda JP, Broeders IAMJ (2009) Ergonomics, user comfort and performance in standard and robot-assisted laparoscopic surgery *Surg Endosc* 23:1365-1371.

[30] Balch CM, Freischlag JA, Shanafelt TD (2009) Stress and burnout among surgeons *Arch Surg* 144:371-376.

[31] Szafranski C, Kahol K, Ghaemmaghami V, Smith M, Ferrara J (2009) Distractions and surgical proficiency: An educational perspective *Am J Surg* 198:804-810.

[32] Vine SJ, McGrath JS, Bright E, Dutton T, Clark J, Wilson MR (2014) Assessing visual control during simulated and live operations: Gathering evidence for the content validity of simulation using eye movement metrics *Surg Endosc* 28:1788-1793.

Table 1. The workload, mental effort, performance, and gaze control data for the ball pick-and-drop task using the robotic and laparoscopic systems.

Variable	Robotic System		Laparoscopic System		
	Mean	***SD***	***Mean***	***SD***	***P value***
Workload					
Total Workload (0-600)	70.28	42.31	91.28	50.01	.002
Mental Demands (0-100)	14.84	16.98	18.50	15.99	NS
Physical Demands (0-100)	5.09	10.42	5.75	8.55	NS
Temporal Demands (0-100)	22.91	22.70	28.53	23.47	NS
Task Complexity (0-100)	9.06	9.02	9.22	10.32	NS
Situational Stress (0-100)	14.47	12.35	21.56	16.71	.036
Distractions (0-100)	3.91	9.89	7.72	18.08	NS
Mental Effort					
RSME (0-150)	31.25	19.43	44.28	19.80	.000
SDNN (ms)	81.28	24.93	75.60	23.47	NS
Task Performance					
Completion Time (s)	35.76	12.56	34.40	11.55	NS
Number of Errors (0-6)	0.53	0.62	1.14	0.66	.001
Gaze Control					
Fixation Rate (Fix/Min)	64.73	23.61	26.23	9.60	.000

Table 2. The workload, mental effort, performance, and gaze control data for the rope threading task using the robotic and laparoscopic systems.

Variable	**Robotic System**		**Laparoscopic System**		
	Mean	***SD***	***Mean***	***SD***	***P value***
Workload					
Total Workload (0-600)	92.66	55.29	120.84	57.50	.001
Mental Demands (0-100)	22.31	20.44	26.59	23.64	NS
Physical Demands (0-100)	5.84	8.39	15.13	13.75	.000
Temporal Demands (0-100)	23.63	19.05	25.78	21.85	NS
Task Complexity (0-100)	23.00	19.62	29.72	17.43	.045
Situational Stress (0-100)	16.34	13.60	19.59	17.65	NS
Distractions (0-100)	1.53	3.26	4.03	13.39	NS
Mental Effort					
RSME (0-150)	43.78	23.12	57.44	21.74	.000
SDNN (ms)	80.14	57.84	65.93	26.30	NS
Task Performance					
Completion Time (s)	72.91	25.64	99.68	41.77	.000
Gaze Control					
Fixation Rate (Fix/Min)	58.30	28.89	20.64	12.00	.000