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Ergonomics of minimally invasive surgery: an analysis of muscle effort and fatigue in the operating room between laparoscopic and robotic surgery

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Abstract

Background Our aim was to determine how objectively-measured and self-reported muscle effort and fatigue of the upper-limb differ between surgeons performing laparoscopic (LAP) and robotic-assisted (ROBOT) surgeries.

Methods Surgeons performing LAP or ROBOT procedures at a single-institution were enrolled. Objective muscle activation and self-reported fatigue were evaluated, and comparisons were made between approaches. Muscle activation of the upper trapezius (UT), anterior deltoid (AD), flexor carpi radialis (FCR), and extensor digitorum (ED) were recorded during the surgical procedure using Trigno wireless surface electromyography (EMG). The maximal voluntary contraction (MVC) was obtained to normalize root-mean-square muscle activation as $\%MVC_{RMS}$. The median frequency (MDF) was calculated to assess muscle fatigue. Each surgeon also completed the validated Piper Fatigue Scale-12 (PFH-12) before and after the procedure for self-perceived fatigue assessment. Statistical analysis was done using SAS/STAT software, with $\alpha = 0.05$.

Results 28 surgeries were recorded (LAP: $N = 18$, ROBOT: $N = 10$). EMG analysis revealed the ROBOT group had a higher muscle activation than LAP for UT (37.7 vs. 25.5, $p = 0.003$), AD (8.9 vs. 6.3, $p = 0.027$), and FCR (14.4 vs. 10.9, $p = 0.019$). Conversely, LAP required more effort for the ED, represented by a significantly lower MDF compared to the ROBOT group $(91.2 \pm 1.5\ \text{Hz vs. } 102.8 \pm 1.5\ \text{Hz}, p < 0.001)$. Survey analysis revealed no differences in self-reported fatigue before and after the surgery between approaches, $p = 0.869$.

Conclusions Our analysis revealed surgeons show similar fatigue levels performing the first case of the day using either robotic or LAP surgery. Surgeons performing LAP surgery had more fatigue in the forearm, robotic surgery required more shoulder and neck use, but neither was superior. Neither technique produced significant overall fatigue on survey. Long-term selective use of these different muscles could be correlated with different patterns of injury. Future studies are needed to fully understand long-term implications of prolonged surgery on occupational injury.

Keywords Ergonomics · Robotic surgery · Electromyography · Minimally invasive surgery

There has been an increase in minimally invasive surgical procedures (MIS) in the past decades. Despite offering improved outcomes to the patient, such as lower postoperative complication and readmission rates, and shorter length of hospital stay, MIS presents unique cognitive and

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ergonomic challenges to the surgeon [1–3]. Studies have shown an increased workload and evidence of injury on a number of muscle groups in the upper body, shoulder, and neck in surgeons occurring from prolonged operative laparoscopic (LAP) procedures [4–6].

As laparoscopy has been in use for over 20 years, robotic surgery has been gaining increasing popularity in recent years, especially in the fields of urology and obstetrics and gynecology, where technology has enabled conventional open procedures to become minimally invasive [7]. Over the last few decades in general surgery, there has been a shift in surgical approach from open to laparoscopy, and more recently to the robotic-assisted. Robotic systems, such as the da Vinci® Surgical System, were originally developed to overcome surgical disadvantages associated with traditional MIS surgery, such as the decreased range of motion, fulcrum effect in instrumentation, elimination of tremor motion, and improve surgical ergonomics [3, 8]. With the advances in MIS techniques along with the positive outcomes of reduced perioperative morbidity, enhanced postoperative recovery, and improved cosmetic over standard open surgical techniques, there has been a shift in the utilization of surgical approaches [3, 7].

Ergonomics is a relatively new but growing emphasis in the field of MIS, and plays an important role in the decision of surgical approach. However, performing MIS procedures can still be physically detrimental to surgeons, and this has been noted in the literature since the beginning of the adoption of LAP techniques [1, 9]. Manufacture of robotic systems claim that the different operating position, which typically involves sitting at a robotics console, is safer for the surgeon from the standpoint of injury fatigue and muscle exertion when compared to surgeons performing laparoscopy [10].

However, limited studies have been conducted by comparing the ergonomics between LAP and robotic surgery, in which the majority adopts testing models or inanimate simulations, and just few assessing surgeons during real time surgery [6, 8, 11, 12]. A better understanding of surgeon's muscle demands and fatigue may lead to the development of improved ergonomics in LAP and robotic surgeries, resulting in better efficiency of the surgeon and enhanced outcomes for the patient in the operating room.

The aim of this study was to determine how objectively-measured and self-reported muscle effort and fatigue of the upper-limb differ between LAP and robotic-assisted (ROBOT) surgical approaches in the operating room.

Materials and methods

This study was approved by the institutional review board at University of Nebraska Medical Center. Surgeons (clinical fellows or attending physicians) performing either LAP
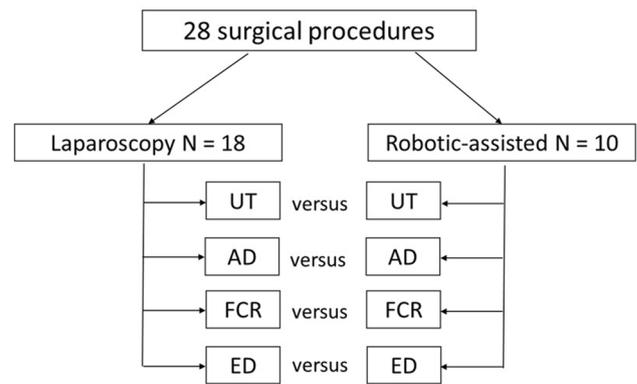

Fig. 1 Methodology applied in this study for comparison between surgical approaches

or ROBOT surgical approach at a single-institution were enrolled in this study from June/2017 to Aug/2017. Surgeons in the fields of general surgery, obstetrics and gynecology, urology, transplant and colorectal who are past their learning curve for the specific approach performed were enrolled. Learning curve was defined as having performed more than 100 cases in the specific approach. Both objective muscle activation and self-reported fatigue were evaluated in all participants, using electromyography (EMG) and a validated survey, respectively. Participants who had a recent muscle-related injury of the upper-limb or that did not complete at least 50% of the survey were excluded from this study. Surgical procedures were identified in the operating room schedule, and surgeons were contacted previously for signing the consent. To avoid any accumulative fatigue throughout the day and eliminate this confounding effect, we only assessed surgeons during the performance of their first surgical case of the day.

Outcomes measured

Surgeon demographics, such as age, gender, and hand dominance were collected. Years of practicing after residency, level of practice, specialty, average of cases performed per month, and distribution of practice amongst approaches were also inquired. Information related to surgical data were also collected, including type of procedure, and operative time.

Objective muscle activation

The Trigno wireless surface EMG (Delsys, Inc., Natick, MA, USA) was adopted to record muscle activations of upper trapezius (UT), anterior deltoid (AD), flexor carpi radialis (FCR), and extensor digitorum (ED) (Fig. 1). Skin preparation was done by scratching and cleaning the target area using 70% isopropyl alcohol pad. Each surface EMG sensor consists of four silver bars which were affixed

perpendicularly to muscle fibers. The resting EMG was recorded while participants were sitting with both hands on the lap. Following that, the maximal voluntary contraction (MVC) of each muscle was performed before surgical scrub and procedures. Raw EMG signals were recorded with the sampling rate of 2000 Hz and were processed using a band-pass filter of 20–300 Hz. Next, the filtered EMG was smoothed by an algorithm with a 150 ms moving window and were computed as a root-mean-square (RMS) EMG. To reduce the inter-subject variation, all RMS EMG were subtracted by resting EMG and normalized by MVC and presented as $\%MVC_{RMS}$ [11, 13]. The median frequency (MDF) of the electromyographic signals from the muscles involved was assessed for measuring muscle fatigue during static force exertion. A decreased MDF of the power spectrum correlates with an increased muscle fatigue [11]. For both groups, EMG records were recorded throughout the surgical procedure only when specific surgical subtasks, including dissection, retraction and suturing were being performed. In the ROBOT group, only portions of the procedure performed with the assistance of the robot were included in the analysis.

Self-reported fatigue

Each surgeon also completed the validated Piper Fatigue Scale-12 (PFH-12; Online Appendix) before and after the surgical procedure for self-perceived fatigue assessment. The survey was administered using the REDCap platform and included both PFH-12 and demographic information. The PFS-12 has four subscales (behavioral, affective, sensory, and cognitive), and a total 10-scale score, with 0 meaning no fatigue. The score calculation was previously reported by Reeve et al. [14].

Statistical analysis

Data are presented as frequencies for categorical data, and mean ± standard deviation or median for the continuous data which were also examined for outliers. Muscle effort and fatigue of the upper-limb from each muscle group were defined: UT, AD, FCR, and ED (Fig. 1). Two methods of surgeries, LAP and ROBOT, were performed by different surgeons, and thus treated as a fixed factor within subjects. The duration of each surgery was divided into four quartiles (Q1–Q4) and treated as a fixed factor within subjects. Repeated measures analysis of variance (RMANOVA) model was used for analysis of the differences across the first and fourth quartiles for MDF and $\%MVC_{RMS}$. Differences of the means for muscle effort and fatigue were compared between the two surgical approaches, averaged over the quartiles. Due to the bounded nature of the $\%MVC_{RMS}$ data, the arcsin transformation was applied in order to attain a

distribution of the residuals that are closer to normal. Means and confidence intervals in the original scale are obtained with a back-transformation. Finally, the results of the survey from before and after the surgical procedure were compared between surgical approaches. All statistical significance tests for differences in means were two-sided, and the alpha level was set as 0.05. Statistical analyses were generated with PROCs MIXED and GLIMMIX from SAS/STAT software Version 9.4 (Cary, NC, USA).

Results

A total of 16 surgeons were enrolled in this study, with 50% being females, mean age of 41 ± 6.2 years, and 92.9% were right-handed. Surgical specialties included colorectal ($N = 1$), general surgery ($N = 3$), Ob/GYN ($N = 3$), MIS/bariatrics ($N = 4$), transplant ($N = 2$), and urology ($N = 3$). Twenty-eight surgeries were recorded (LAP: $N = 18$, ROBOT: $N = 10$).

Among all surgical procedures recorded, eight were related to foregut (LAP: $N = 6$, ROBOT: $N = 2$), eight to hernia repairs (LAP: $N = 5$, ROBOT: $N = 3$), four to bariatric procedures (LAP: $N = 4$), three to Ob/GYN (LAP: $N = 1$, RA: $N = 2$), two to urology (RA: $N = 2$), and three others (LAP: $N = 2$, ROBOT: $N = 1$) including kidney transplant, hepatectomy, and rectopexy. Median operative room time was similar between LAP [212 min (151–360 min)] and ROBOT [240 min (165–278 min)], $p = 0.464$. There were no conversions to open procedures in either group.

EMG analysis

Evaluation of $\%MVC_{RMS}$ between two surgical approaches revealed that the ROBOT had a higher muscle activation than LAP for UT (37.7 vs. 25.5, $p = 0.003$), AD (8.9 vs. 6.3, $p = 0.027$), and FCR (14.4 vs. 10.9, $p = 0.019$). Activation of ED was similar between the two surgical approaches, $p = 0.085$ (Fig. 2).

Evaluation of MDF between two surgical approaches revealed that the ED demonstrated a lowered MDF in LAP (91.2 ± 1.5 Hz) than in the ROBOT (102.8 ± 1.5 Hz), $p < 0.001$. MDF levels of UT ($p = 0.190$), AD ($p = 0.066$), and FCR ($p = 0.170$) were similar between the two groups (Fig. 3).

Assessment of fatigue levels over time, the difference between Q4 and Q1, revealed that the change in fatigue levels throughout the surgery was similar between the two surgical approaches for all four muscle groups evaluated, all $p > 0.05$ (Fig. 4). Similarly, differences of muscle activation over time were similar between the two surgical approaches (Fig. 5).
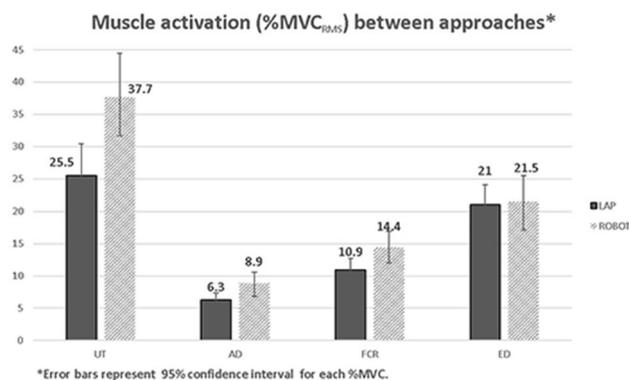
Muscle activation (%MVC$_{RMS}$) between approaches*

Fig. 2 Muscle activation (%MVC$_{RMS}$) of muscles, between LAP and robotic-assisted (ROBOT) procedures*. *UT* upper trapezium, *AD* anterior deltoid, *FCR* flexor carpi radialis, *ED* extensor digitorum
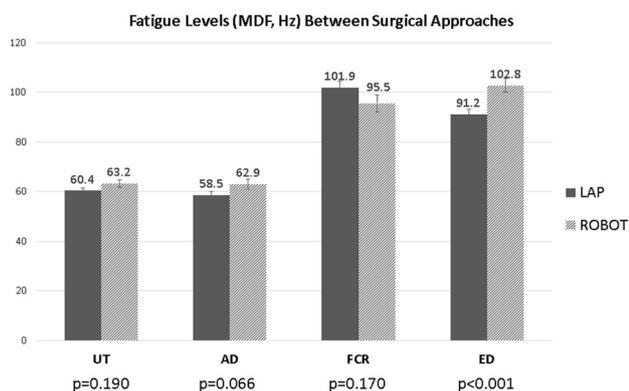
Fatigue Levels (MDF, Hz) Between Surgical Approaches

Fig. 3 Fatigue levels (MDF) of muscles, between LAP and ROBOT procedures. *UT* upper trapezium, *AD* anterior deltoid, *FCR* flexor carpi radialis, *ED* extensor digitorum

By looking at each approach individually, our analysis showed that the UT had the highest activation level when compared to the other muscle groups for both LAP and ROBOT, ($p < 0.001$; Fig. 6). Our data also revealed that shoulder muscles (i.e., UT and AD) had lower MDF than wrist muscles (i.e., FCR and ED) in both LAP ($p < 0.001$) and ROBOT ($p < 0.001$) groups (Fig. 7).

Self-reported fatigue

Survey analysis revealed no differences in self-reported fatigue before and after the surgery in LAP (preoperative: 2.60 ± 1.49, postoperative: 2.91 ± 1.11, $p = 0.322$) and ROBOT (preoperative: 2.33 ± 1.47, postoperative: 2.77 ± 1.25, $p = 0.132$). There were also no significant differences between the two surgical approaches, $p = 0.869$. Upon evaluation of the four subscales, a significant increase in self-reported fatigue related to the behavior subscale was seen after the surgery for both surgical approaches

(preoperatively: 2.17 ± 1.27; postoperatively: 2.62 ± 1.17, $p = 0.018$). The affective, sensory, and cognitive subscales were similar between the two groups. The behavior subscale portion of the survey evaluates levels of fatigue interference with tasks and work, as well as fatigue intensity. An increase in the behavior subscale is related to increased mental exhaustion of the task performed (Table 1).

Discussion

The analysis of the electromyographic data present in this study revealed that different muscle groups are preferentially activated in the performance of LAP compared to ROBOT surgical approaches in the operation room. Overall, muscle groups representing shoulder and neck muscles had a higher fatigue level than muscle groups of the wrist. Still, UT was found to have the highest activation levels when compared to other muscle groups. Comparisons between the two surgical approaches revealed that LAP surgeons tended to have a higher fatigue level of the extensor of the wrist compared to surgeons performing robotic-assisted surgeries. In contrary, shoulder and neck muscles, as well as wrist flexors had a higher activation level in the robotic group. Despite of the different fatigue levels presented, surgeons did not report worsening of their fatigue after finishing the first surgical procedure of the day.

Historically, surgeon strain related to performing MIS procedures has been reported to be < 20% [1]. However, recently studies have shown that over 80% of surveyed LAP surgeons reported significant discomfort and injury related to their occupation, and that the strongest predictor of reported injury was a high surgical case volume [15]. An analysis of occupational injury prevalence in plastic surgeons revealed a similar self-reported injury, with more than 80% of respondents reporting at least one musculoskeletal injury. The most prevalent injuries found were muscle strain and cervical spine pain being indicated in nearly 65% and 25% of respondents, respectively [4]. Most recently, a survey of 127 MIS surgeons in the Netherlands showed high rates of musculoskeletal complaints, especially in the neck (39.5%), erector spinae muscle (34.9%), and right deltoid muscle (18.6%) [6]. The authors also found that 37.5% of the surveyed surgeons were on medication and/or therapy for their injuries, although no difference was seen between minimally invasive and open approaches. Another survey of more than 400 surgeons performing robotic-assisted procedures showed that 56.7% reported physical symptoms or discomfort, including neck stiffness, finger and eye fatigues [16]. In Venezuela, 14 advanced LAP surgeons were evaluated after performing both LAP and robotic inguinal hernia repairs in an inanimate model [12]. The application of the Local Experience Discomfort scale, and the Subjective mental effort
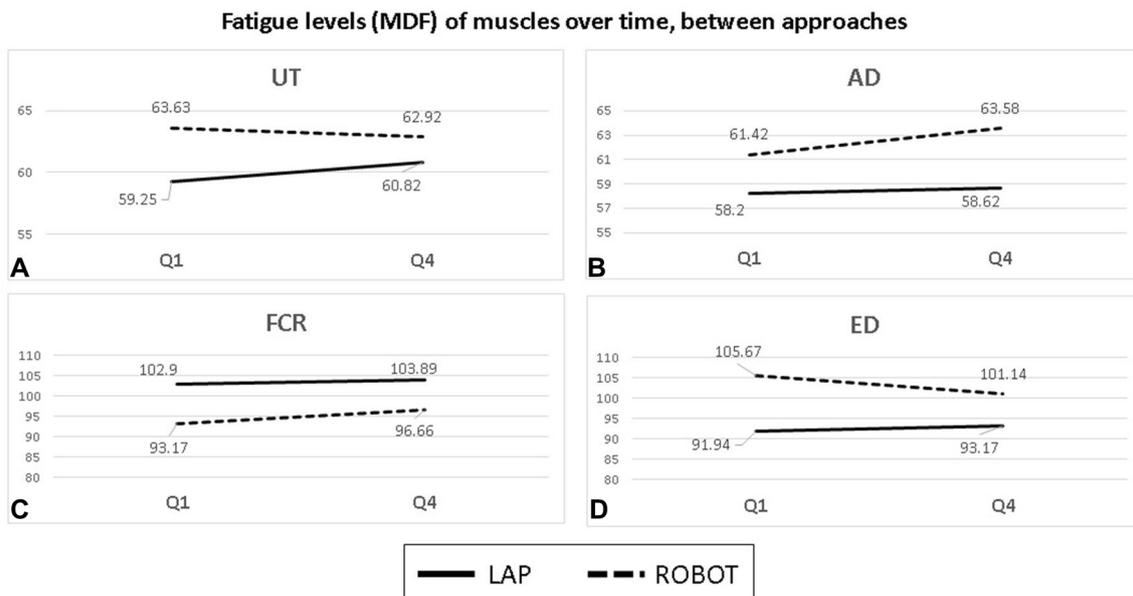
Fig. 4 Fatigue levels (MDF) of muscles over time, between LAP and ROBOT procedures. *p*-values for each graph **A** 0.900, **B** 0.990, **C** 1.000, **D** 0.750. *UT* upper trapezium, *AD* anterior deltoid, *FCR* flexor carpi radialis, *ED* extensor digitorum
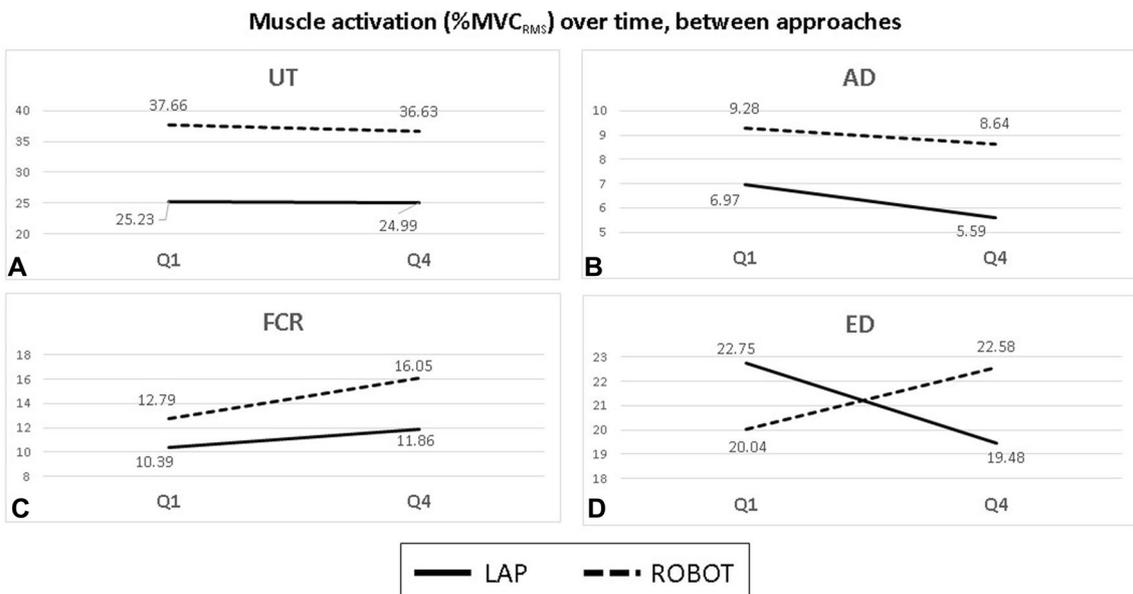

Fig. 5 Muscle activation (%MVC$_{RMS}$) over time, between LAP and robotic-assisted (ROBOT) procedures. *p*-values for each graph **A** 1.000, **B** 0.980, **C** 0.960, **D** 0.460. *UT* upper trapezium, *AD* anterior deltoid, *FCR* flexor carpi radialis, *ED* extensor digitorum

questionnaire revealed that robotic surgeons reported less mental and physical effort when compared to laparoscopy [12]. Another study analyzed the self-perceived fatigue of chief and assistant surgeons performing LAP and robotic-assisted procedure using three different questionnaires [17]. Chief surgeons performing robotic procedures had a higher functional fatigue at the end of surgery compared to LAP group, which was significant for the Profile of Mood States and Visual Analogue Scale questionnaires. The authors also applied the Quick Questionnaire Piper Fatigue Scale, but no statistical significances were seen between the groups [17]. Interestingly, results from the Piper Fatigue Scale in the current study demonstrated that the surgeons indeed experienced increased levels of mental workload after performing
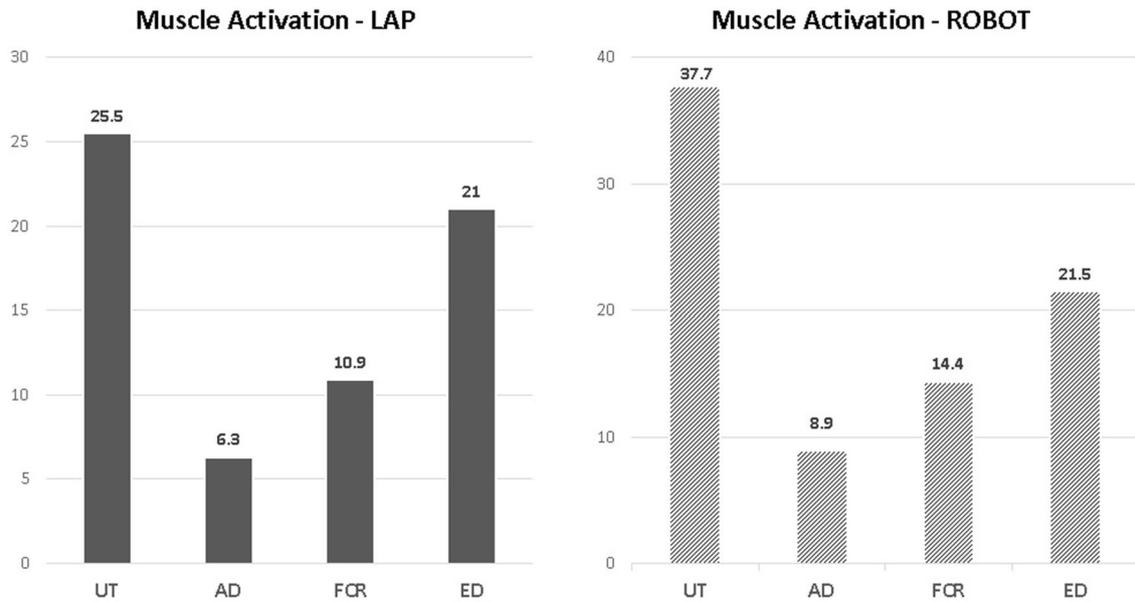
Fig. 6 Muscle activation (%MVC_{RMS}) of muscles within each surgical approach. All $p < 0.001$. *LAP* laparoscopy, *ROBOT* robotic-assisted, *UT* upper trapezium, *AD* anterior deltoid, *FCR* flexor carpi radialis, *ED* extensor digitorum

Fig. 7 Fatigue levels (MDF) of muscles within each surgical approach. All $p < 0.001$. *LAP* laparoscopy, *ROBOT* robotic-assisted, *UT* upper trapezium, *AD* anterior deltoid, *FCR* flexor carpi radialis, *ED* extensor digitorum
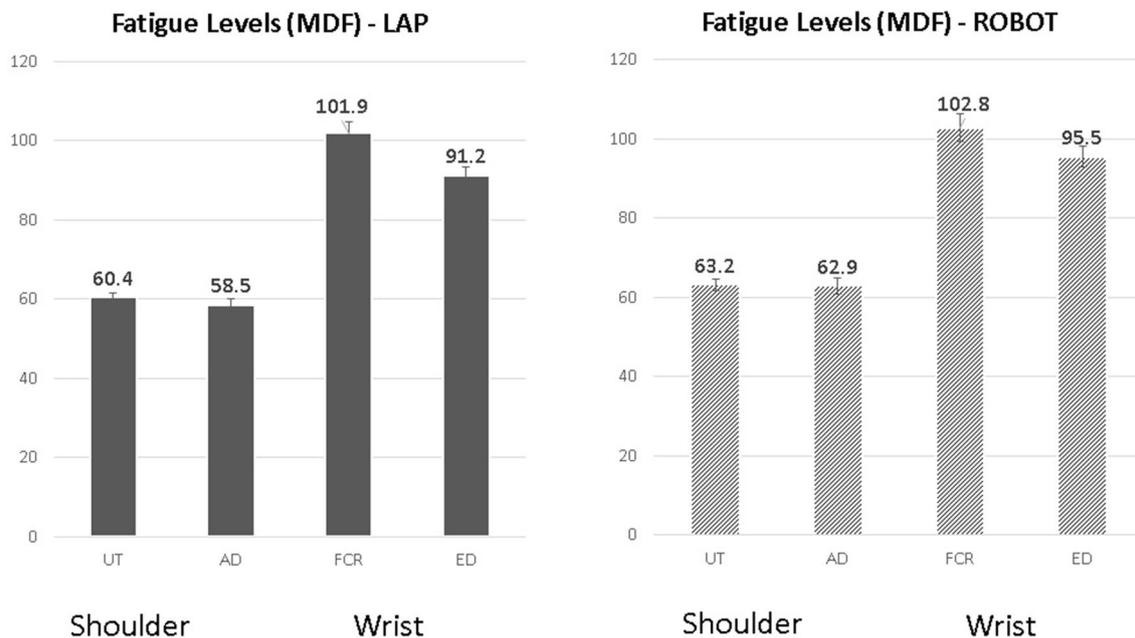
LAP and robotic surgeries, compared to their scores taken prior to the surgery. However, this increase was also not statistically different between the two surgical approaches.

In spite of this accumulating knowledge, few studies have been conducted comparing ergonomics in LAP, and robotic-assisted surgical approaches [12, 17]. In our previous studies examining muscle fatigue and improvement in surgical skills between LAP box-trainer and virtual reality training in a laboratory setting [18, 19], we found that muscle fatigue was similar between LAP and virtual training environments for the tested training tasks, but muscle activation differed among the tasks for the tested muscle groups [18,

Table 1 Scores of PIPER Fatigue Scale (PFS-12) before and after surgery

	LAP			ROBOT			p value between approaches
	Before surgery	After surgery	p value	Before surgery	After surgery	p value	
Overall score	2.60 ± 1.49	2.91 ± 1.11	0.322	2.33 ± 1.47	2.77 ± 1.18	0.132	0.869
Subscales							
Behavioral	2.24 ± 1.17	2.65 ± 0.91	0.079	2.03 ± 1.49	2.57 ± 1.59	0.149	0.857
Affective	3.07 ± 2.17	3.4 ± 1.67	0.328	2.37 ± 2.28	2.9 ± 2.07	0.117	0.860
Sensorial	2.78 ± 1.90	3.05 ± 1.17	0.470	2.57 ± 1.66	2.8 ± 1.18	0.539	0.959
Cognitive	2.31 ± 1.76	2.53 ± 1.25	0.632	2.37 ± 1.79	2.8 ± 1.08	0.282	0.802

Comparisons performed between and within LAP and robotic-assisted procedures

LAP laparoscopic procedures, *ROBOT* robotic-assisted procedures

19]. However, these studies did not include robotic tasks as a comparative group, and only recruited undergraduate and medical students as test subjects, and these untrained subjects would likely have differing muscle activation relative to a trained surgeon or fellow. In another study, we found that performance is different between novices and experts during robotic training tasks in a laboratory setting [20].

Wang et al. used EMG to evaluate muscle activation between surgeons performing LAP and open sigmoid colectomies [2]. Despite not including robotic procedures in their analysis, the authors reported that the UT had the highest mean muscle activation in both open and LAP approaches [2]. We have previously reported similar findings upon evaluation of the upper-limb of six subjects performing fundamental surgical training tasks using a virtual simulation trainer [21]. A U-shaped pattern distribution for muscle activation was seen, representing an increase in muscle activity of proximal and distal muscle groups, such as UT and ED [21]. This would suggest those muscle groups to be prime movers in the performance of surgical tasks. Likewise, in our current analysis, shoulder muscle groups (i.e., UT and AD) tended to reach fatigue easily than muscle groups in the wrist (i.e., FCR and ED), in surgeons performing both LAP and ROBOT surgeries. Shoulder muscles are known to be used for posture stabilization, which plays an important role in performing tasks more consistently and accurately [13]. This is true for both standing and sitting positions, in LAP and ROBOT respectively, performed in the operating room. Another hypothesis for the highest activation seen in the trapezius muscle compared to the other muscle groups studied could be due to the awkward sitting posture [22] that increased tension caused by remote vision or arm manipulation on the arm rest.

Posture has not only been proven to have an impact in the ergonomics of the body of surgeons performing surgical tasks, but could also explain the different patterns of muscle activation and fatigue seen between different surgical approaches [23–25]. A comparison of seven surgeons performing both LAP and robotic single site digestive and urological surgeries in a porcine model demonstrated that ROBOT offered better ergonomics when compared to LAP, due to the decreased extension of elbow and flexion of the shoulder [23]. A record of 18 surgeons performing LAP gynecologic surgery revealed important factors that increased the risk of musculoskeletal injuries, and they were all associated with mal-positioning of the body during the surgery, including neck rotation and asymmetrical loading between shoulders [24]. Another study comparing ergonomics in LAP and robotic-assisted bariatric surgery found that while LAP surgery can cause discomfort in the upper back, shoulders, arms, and wrists, robotic surgery can lead to increased discomfort in the neck and trunk of the surgeon [25]. Similarly, in our study, surgeons performing robotic-assisted procedures required more muscle effort of shoulder and neck muscle groups compared to LAP surgeons. Still, the LAP group had a higher fatigue level in the extensor of the wrist, whereas the wrist flexors were more active in the ROBOT group. The higher fatigue level seen in the ED could be explained by maintaining the "claw hand" posture using LAP instruments [26, 27].

The predominant activation of different muscle groups between the two surgical approaches observed in our analysis could be due to differences in ergonomic design between LAP and robotic platforms. The later one has been designed to provide higher number of degrees of freedom, and better precision through high resolution 3D visualization, tremor filtration, motion scaling, and a comfortable user interface, mimicking the human normal physiology [3]. While the surgical subtasks and instrument design required in laparoscopy could explain the higher fatigue level seen in wrist extensors. Another speculation is that surgeons are underutilizing the ergonomics advantages of robot, including the arm rest, adjustment of the chair or of the console level, which could explain the reason for the higher activation of ADs in the ROBOT group. Whenever the work environment is not optimized,

it leads to a poor surgeon's posture, leading to unnecessary muscular recruitment.

Given the evidence in musculoskeletal injury in the surgeons, the findings of the current study just reemphasize the importance of the ergonomics awareness by surgeons. A few groups have already started seeking solutions to this issue [28]. Park et al., demonstrated the efficacy of pre-planned breaks during LAP surgery, with surgeons reporting enhance performance, less pain and fatigue, as well as an increase in focus after taking those micro breaks [28]. There is also a clinical trial in progress evaluating possible changes in measurement of console settings, and head angle for the robotic platform [29].

This study has several limitations, such as the limited sample size and lack of randomization between groups. Also, we only evaluated the muscle effort and fatigue of upper-limb of the surgeons. Therefore, we have no information related to the muscle groups of the back. Furthermore, the changing in fatigue levels over time was similar between the two surgical approaches in our study. A possible explanation is the inclusion of the first case of the day only. Surgeons fatigue levels (as measured by EMG) after performing surgical cases have been previously shown to not achieve significance, due to a lack of muscle activation needed to reach exhaustion [17]. We believe that there was not enough time for the surgeons to reach overall significant fatigue levels, due to the record of the first surgical case of the day.

In conclusion, no difference was observed in self-reported fatigue between the two groups. Surgeons show similar levels of fatigue while performing the first case of the day using either robotic or LAP surgery. Surgeons performing LAP surgery tended to have more fatigue in the forearm muscles, while robotic surgery required more shoulder and neck muscles. Neither technique produced significant overall fatigue on survey. Ergonomics of standing surgeon favored a different set of muscles when compared to ergonomics of sitting surgeons, but no position was found to be superior. Long-term selective use of these different muscles could be correlated with different patterns of injury. However, future studies are needed to fully understand long-term implications of prolonged surgery on occupational injury, and the prevalence of injury among MIS surgeons.

Compliance with ethical standards

Disclosures Dmitry Oleynikov is the shareholder of Virtual Incision Corporation. Priscila Rodrigues Armijo, Chun-Kai Huang, Robin High, Melissa Leon and Ka-Chun Siu have no conflicts of interest or financial ties to disclose.

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