The Surgeon 23 (2025) 257–264

Contents lists available at ScienceDirect

The Surgeon

journal homepage: www.thesurgeon.net

Strain on the surgeon: a systematic review of the methods of measuring strain in abdominal and thoracic surgery

Nainika Menon [a], Nadia Guidozzi [b], Sivesh Kathir Kamarajah [c], Rohan Gujjuri [d], Sheraz R. Markar [a,*]

[a] Surgical Intervention Trials Unit, Nuffield Department of Surgical Sciences, University of Oxford, Oxford, United Kingdom
[b] Department of General Surgery, University of Witwatersrand, Johannesburg, Republic of South Africa
[c] NIHR (National Institute for Health and Care Research) Doctoral Fellow, NIHR Global Health Research Unit on Global Surgery, School of Health Science, University of Birmingham, United Kingdom
[d] College of Medical and Dental Sciences, University of Birmingham, Birmingham, United Kingdom

ARTICLE INFO

Handling editor: D.G. Healy

Keywords:
Strain
Surgeon

ABSTRACT

Introduction: Surgery can be arduous to the operating surgeon – both in terms of cognitive and physical strain. Ergonomic strain has been recognised to drive absenteeism, reduce career longevity and cause injuries.
This systematic review aims to 1. Outline the nature of ergonomic strain in the context of abdominal and thoracic surgery, regardless of surgical approach 2. Identify the qualitative and quantitative measures of surgical strain.
Methods: A systematic review was conducted using Pubmed, MEDLINE and Ovid EMBASE databases (date range: 1990 to Sep 2024). Of the initial 1288 articles identified, a final 71 studies were included in this review (quantitative measures = 36, qualitative measures = 49, of which 14 studies overlapped with the papers reviewed in the quantitative measures section).
Results: The quantitative measures used to measure ergonomic strain included electromyography, electrocardiography, gravimetric position sensors, skin conductance and inertial measurement units. Laparoscopic surgery caused less physical strain than open surgery, however more cognitive strain during the learning curve. Robotic surgery yielded conflicting data in terms of muscle activation when compared to laparoscopic surgery however reported less cognitive and cardiovascular strain. The qualitative measures of strain included a range of self-reported questionnaires, demonstrating important gender differences and scores that typically correlated with objective physical strain.
Discussion: The studies show wide variation in measuring ergonomic strain. Avenues for further research include measuring the impact of learning curves, patient factors on ergonomic strain and the impact of gender.

1. Introduction

The risk of musculoskeletal injuries amongst healthcare professionals is a well-established issue, particularly impacting the neck, lower back and shoulders [1–4]. Surgery requires long hours of operating, often in unnatural positions, with notable physical and mental strain. The ergonomic stress experienced by surgeons while operating has been identified as a major cause of absenteeism in the workplace and an important factor in reducing surgical career longevity [1]. For those without a specific isolated injury, chronic fatigue and pain from years of operating can have a significant impact on surgeons, including early retirement [1].

There has been a clear interest in identifying risk factors for injuries to the surgeon during operative procedures, and a focus on comparing open and minimal invasive surgery for these at-risk behaviours. With the expanding realm of minimal invasive surgery, laparoscopic, robotic and endoluminal/endovascular surgery can possibly offer improved ergonomics for surgeons, particularly with an increasing overweight population. Whilst laparoscopic surgery offers many benefits to the patient, it is thought to increase cognitive strain on the surgeon, thereby potentially increasing their risk of musculoskeletal injuries due to diverted attention [5–7]. Moreover, robotic surgery is deemed to be less physically demanding for the surgeon offering some improvements to the traditional limitations of laparoscopic surgery, namely decreased range

* Corresponding author. Surgical Intervention Trials Unit, Nuffield Department of Surgical Sciences, University of Oxford, Oxford, United Kingdom.
E-mail address: sheraz.markar@nds.ox.ac.uk (S.R. Markar).

https://doi.org/10.1016/j.surge.2025.04.015
Received 24 December 2024; Accepted 14 April 2025
Available online 30 April 2025
1479-666X/

of motion, fulcrum effect on instrumentation, elimination of tremor motion and improved surgical ergonomics [8,9].

Although there are several studies that evaluate the impact of strain on the surgeon in various subspecialties, there is a lack of an up-to-date systematic review evaluating surgical strain in the context of surgeons operating within abdominal and thoracic cavities. This encompasses a variety of surgical specialties, including general surgery, urology, gynaecology and thoracic surgery; these are typically long operations in deep cavities with significant strain to the surgeon. The aim of this systematic review is to provide an up-to-date summary of the literature exploring the impact of abdominal or thoracic surgery on the surgeon in terms of ergonomic strain.

2. Methods

The systematic review complied with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A systematic review was conducted using Pubmed, MEDLINE and Ovid EMBASE databases (date range: 1990 to Sep 2024) using the following search strategies with standard Boolean operators: 'surgery', 'operation', 'surgeon', 'strain', 'stress', 'ergonomic(s)' (n = 1267). Four reviewers conducted the literature search (NM, NG, SKK, RG) and where there were any discrepancies, a fifth independent reviewer was consulted (SRM). Furthermore, the reference lists of the included articles and review articles were searched for additional studies (n = 21).

This initial search yielded 1288 articles. Studies were screened to include only abdominal or thoracic surgery, regardless of surgical approach (endoscopic, laparoscopic, robotic and or open). Surgical simulation was also included as many such studies explored the impact of ergonomic changes such as table height and type of instrument on surgeon strain. Only English language studies were included in this study.

The articles were reviewed based on title and abstract, resulting in 132 articles. 5 articles were excluded as the research team were unable to find full-text articles for this, despite thorough search strategies. Further articles were eliminated based on operative speciality, for describing transvaginal approaches as part of gynaecological surgery, skill performance is medical students rather than surgeons or emphasise technology development to measure strain (e.g. wearable devices). 71 articles were included in the final review once full-text articles were screened. The search strategy has been outlined in the PRISMA flowchart below (Fig. 1).

3. Results

The results have been divided into subsections describing the quantitative and qualitative measures of strain experienced by the surgeon.

3.1. Quantitative measures of strain

3.1.1. Reporting methods and domains

A total of 36 papers were identified that quantitatively assessed strain using various techniques, such as EMG recording or inertial measurement units (IMUs). There were 17 papers that reviewed muscle strain in a simulated environment versus 20 studies conducted during real time surgical procedures. Table 1 outlines these articles further.

3.1.2. Surgical specialties, techniques and impact on surgeons

Quantitative measures of strain have been studied across several surgical specialties, including general surgery and its subspecialties, urology, vascular surgery and gynaecology. The general surgical operative approaches were either open, laparoscopic, endoscopic or robotic. Vascular surgery included endovascular surgery. A number of studies were based on simulated environments to safely study variations such as table height or laparoscopic monitor position.

3.1.2.1. Open surgery. Open surgery tended to be more physically demanding than minimally invasive surgery. Open surgery was shown to have larger neck and torso angles when compared to laparoscopic surgery, with increased time spent in high-risk postures with one study showing median percentage procedural time for the surgeon in these positions being 66 % for the neck and 24 % for the torso [8,11]. On average, surgeons spent more time with their neck flexed during open surgery (147 min) compared to robotic procedures (68 min), which was associated with increased pain during self-reported questionnaires (discussed in the 'Qualitative Measures' section below. [18]. There was also increased torso and neck muscle activation within the trapezius and erector spinae muscles in open surgery compared to laparoscopic surgery, with less muscle rest time and higher sustained low muscle activity. Open surgery leads to increased physical workload [7,14,15].

3.1.2.2. Laparoscopic surgery. Laparoscopic surgery has been associated with a higher fatigue level of the extensors of the wrist compared to robotic surgery, however shoulder and neck muscles as well as wrist flexors had a higher activation during robotic surgery [9]. Wang et al.

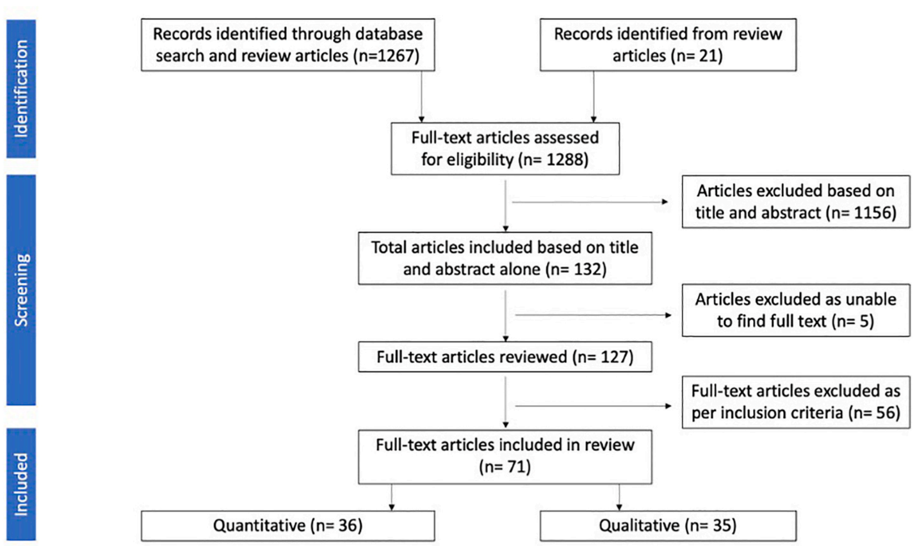

Fig. 1. (legend): PRISMA flowchart demonstrating search strategy.

Table 1
Summary of the quantitative studies included in the review.

Study name	Reporting type	Surgery type	Surgical approach	Number of surgeons, n
Armijo 2019 [9]	EMG	Colorectal, general surgery, bariatrics, urology, transplant	Laparoscopy, robotic	16
Armijo 2022 [10]	EMG	Colorectal, general surgery, bariatrics, urology, transplant	Laparoscopy, robotic	16
Davila 2020 [11]	IMU	Vascular	Open, endovascular	16
Dalager 2020 [12]	EMG	Colorectal	Laparoscopic, robotic	13
Yang 2021 [8]	IMU	Colorectal, head and neck, hepato-pancreatico-biliary, general surgery	Open, laparoscopic	24
Thurston 2022 [13]	EMG	Foregut surgery	Laparoscopic	5
Norasi 2021 [14]	Postural monitors	Vascular	Open, endovascular	16
Fan 2022 [15]	EMG, IMU	Neck surgery, urology	Open, robotic	22
Abdelrahman 2016 [16]	BodyGuardian Remote Monitoring System (heart rate, salivary cortisol level)	Cholecystectomy	Single incision laparoscopic, conventional laparoscopic	1
Yu 2017 [17]	IMU	Urology – robotic assisted radical prostatectomy	Robotic	10
Bigham 2021 [18]	IMU	Urology	Open, robotic	30
Heemskerk 2014 [19]	ECG (heart rate and heart rate variability)	Cholecystectomy	Laparoscopic, robotic	2
Kraemer 2018 [20]	EMG, ECG, gravimetrical positional sensors	Hysterectomy	Laparoscopic, robotic	5
Meltzer 2020 [4]	IMU	Cardiothoracics, colorectal, general surgery, gynaecology, head and neck, hepato-pancreatico-biliary, neurosurgery, orthopaedics, plastics, urology, vascular	Open, laparoscopic, endovascular	53
Kramer 2023 [21]	Bipolar surface EMG, 2-dimensional gravimetric position sensors, ECG	Hysterectomy	Laparoscopic, robotic	8
Yang 2020 [22]	IMU	colorectal, cardiothoracic, general surgery, head and neck, HPB transplantation, neurology, obstetrics and gynaecology, orthopaedics, plastics, urology, vascular	Open, laparoscopic and robotic	53
Szeto 2009 [7]	EMG	Open: colectomy, gastrectomy, mastectomy, thyroidectomy, aneurysmorrhaphy, hepatectomy, liver transplant. Endovascular: percutaneous transluminal angioplasty, carotid stenting, aortic stent graft repair. Laparoscopic: cholecystectomy, appendicectomy, colectomy, hernoplasty	Open, laparoscopic and endovascular	25
Nguyen 2001 [6]	Video analysis of body movements using predefined criteria from Department of Physical Therapy	Abdominal surgery (Laparoscopic: oesophagectomy, Roux-en-Y gastric bypass, sigmoid colectomy, staging for oesophageal cancer, cholecystectomy Open: pancreaticoduodenectomy, Roux-en-Y gastric bypass, sigmoid colectomy, ventral hernia repair, inguinal hernia repair	Laparoscopic, open	5
Lawson 2006 [23]	RULA	Roux-en-Y gastric bypass	Laparoscopic, robotic	1
Manasnayakom 2009 [24]	EMG	Simulation, table height adjustments	Laparoscopic	10
Matern 2004 [25]	EMG	Simulation, monitor positions	Laparoscopic	18
Van der Schatte 2009 [26]	Ambulatory monitoring system - mean square of successive difference between consecutive heartbeats (low value mean high stress), pre-ejection period, average heart rate	Simulation, table height adjustments	Laparoscopic, robotic	16
Berquer 2001 [27]	EMG, skin conductance, accelerometer/gravitometer sensor	Simulation, varying table heights	Laparoscopic	21
Berguer 1999 [28]	EMG	Simulation	Open, laparoscopic	27
Berguer 2001 [29]	EMG	Simulation, varying instrument angulation	Laparoscopic	8
Berguer 2001 [30]	Tonic skin conductance, electro-oculogram	Simulation	Laparoscopic, open	28
Berguer 2003 [31]	EMG	Simulation	Laparoscopic, open	21
Berguer 2006 [32]	Orientation sensor, EMG, skin conductance	Simulation	Laparoscopic, robotic	10
Marquetand 2021 [33]	Orthopaedic goniometer, gravimetric position sensor, EMG, laser doppler flowmetry, tissue spectrometry	Simulation, 25° bent forward maintaining posture (table height adjustments)	Open	12
Wright 2022 [34]	EMG	Simulation, urological procedure (seated and standing position)	Ureteroscopy	3
Morales 2019 [35]	EEG	Simulation	Laparo-endoscopic single site (LESS), multiport laparoscopic surgery	4
Di Stasi 2017 [36]	Wearable eye tracker	Simulation	Laparo-endoscopic single site (LESS), multiport laparoscopic surgery	16
Moore 2015 [37]	Impedance cardiograph (Physioflow)	Simulation	Laparoscopic, robotic	32
Steinhilber 2016 [38]	EMG, wrist angle/posture	Simulation, different instruments (rotatable vs fixed handle), different table heights	Laparoscopic	57
Quick 2003 [39]	EMG	Simulation, different instruments (ratcheted and non-ratcheted instruments)	Laparoscopic	3
Wang 2017 [40]	EMG	Colorectal (sigmoid colectomy)	Open, laparoscopic	1

showed that laparoscopic sigmoidectomies had reduced muscle activation compared to open surgery [40]. This may be due to instrument manipulation largely being performed by the hands and forearm with limited arm and shoulder engagement [40]. Whilst laparoscopic surgery had fewer neck, shoulder and torso movements, it has been shown to require more upper arm angulation and forearm and thumb muscle activation, compared to open surgery [6].

Interestingly, in the context of cholecystectomies, single incision surgery was shown to have a higher change in maximum heart rate, higher salivary cortisol level, increased prefrontal lobe activity and higher gaze entropy, compared to conventional laparoscopic surgery [16,35]. This could be because the former is a less commonly performed and technically more challenging using a single incision.

In a simulated setting, laparoscopic surgery was shown to require more mental concentration, demonstrated by increased skin conductance and eye blink rate [29]. However, notably, this difference was not significant amongst experienced surgeons, suggesting that the learning curve of laparoscopic surgery is likely to cause more cognitive strain in the short term but overall improvement in physical strain once the surgeon was more experienced [29].

3.1.2.3. Robotic surgery. Manufacturers of robotic systems claim that being seated at a console improves surgeon safety with regards to injury fatigue and muscle exertion compared to laparoscopic surgery [9]. Interestingly, Armijo et al. reported that electromyography (EMG) recordings noted to higher muscle activation in robotic surgery compared to laparoscopic surgery for shoulder and neck muscles as well as wrist flexors [9]. Laparoscopic surgery required more muscle activation of extensor digitorum [9]. Kramer at all reported the converse, with lower EMG recorded activation of shoulder and neck muscles in robotic surgery and higher activation of extensor digitorum [21]. Laparoscopic surgery has high static muscle loads for the neck, trunk and legs, which is associated with musculoskeletal pain [12]. As much as the console surgeon is arguably experiencing less physical strain, it has been shown that the assisting 'table' surgeon has more physical demands and strain, with worse neck postures. As expected, the console surgeons experienced more mental strain when compared to their assisting surgeons [17].

Robotic surgery was shown to have lower EMG recordings and lower skin conductance, suggestive of lesser stress compared to laparoscopic surgery in the simulated setting [29]. In a simulated setting, impedance cardiography also showed more healthy, adaptive cardiovascular responses such as a higher blood flow and lower vascular resistance compared to the laparoscopic group [37]. To our knowledge. The effect of familiarity with a procedure on stress has not been fully explored in open vs robotic surgery and would be an area for further study.

3.1.2.4. Simulation. 17 studies used laparoscopic simulation to study musculoskeletal strain and ergonomics amongst surgeons. Adjusting table height and varying monitor position has been shown to impact muscle strain. Berquer (2002), Matern (2004) and Manasnayakom (2009) et al. showed that performing simulated laparoscopic tasks at various monitor positions and table heights can minimise muscle strain, particularly neck strain, demonstrating that the ideal table height is at elbow height [24,25,27]. When the table height is above the elbow, there was increased activation of the deltoids, arm extensors, trapezius and para-spinal muscles, whereas below-elbow table heights caused lower back discomfort and increased workload in arm flexors, as measured by EMG [24,25,27]. However, there was no notable difference in mental strain, as measured by skin conductance and no notable impact on task time [27].

3.1.2.5. Endovascular. Davila et al. showed that vascular surgeons had increased ergonomic postural risk (EPR) scores of the neck and lower back during open vs non-open surgery [11]. The EPR scores of these areas correlated to the survey findings of increased physical demand by the surgeons [11].

3.1.3. Study types and measures of strain

EMG used on specific muscle groups can identify muscle activation during various types of surgery as well as maximal voluntary muscle contraction [9]. Median frequency (MDF) of EMG signals can be used to assess muscle fatigue, with a decreased MDF of the power spectrum correlating with increased muscle fatigue [9].

Inertial muscle unit sensors can be used to measure body posture angles by collecting data from an accelerometer, magnetometer and gyroscope within each sensor. The time spent in a specific range of risk categories for each body segment can be used to stratify risk for ergonomic injury [4]. A modified rapid upper limb assessment (RULA) can also be used to categorise postural angles into high-risk positions. High risk positions refer to $>20^\circ$ for the neck and torso and $>45^\circ$ for both shoulders [8].

Some studies used electrocardiography (ECG) or wearable cardiac monitors to monitor heart rate and rate variability as a measure of cognitive strain or stress. Other wearables such as eye trackers and video analysis of body movements during surgery were used as quantitative measures of ergonomic strain. Electroencephalography (EEG) has also been used sparingly to measure cognitive strain (see Table 1). Whilst skin conductance has been used a measure of mental stress but measuring sympathetic activation, it has limitations as it also increases during attention and focus.

3.1.3.1. Use of adjuncts. More than just the associated postural strain during various surgical procedures, the use of adjuncts such as loupes, headlights and lead aprons can also lead to associated increased muscle strain [4]. Meltzer et al. showed that the use of surgical loupes and headlamps were associated with unfavourable neck positions (with loupes 85,2 % vs without 58.1 % and with headlamps 79.9 % vs without 62.2 %.) [4].

3.2. Qualitative measures of strain

3.2.1. Reporting methods and domains

For the qualitative component of the systematic review, 49 studies were included. Of these 49 studies, 14 studies overlapped with the articles in the quantitative section. These studies summarised different use of reporting measures and impact to surgeons (Table 2).

Most of the studies used self-reported questionnaires to assess a range of ergonomic issues, musculoskeletal symptoms, workload, and discomfort among surgeons. These domains covered were extensive, including visual symptoms, neck and shoulder problems, muscle effort, fatigue, cognitive cost, workload, and intraoperative posture. These self-assessments provided valuable subjective data on the physical and mental strains experienced by surgeons during various surgical procedures. For instance, Bigham et al. utilised self-reported neck pain scores to assess chronic neck pain among surgeons, highlighting the prevalence and impact of such discomfort on surgical performance and career longevity [18]. Similarly, Hotton et al. used Borg's CR-10 scale to quantify the physical exertion and strain experienced by surgeons during standard laparoscopy, underscoring the high levels of physical demand associated with this technique [75].

3.2.2. Surgical specialties and techniques

The studies encompassed a wide array of surgical specialties such as minimally invasive surgery (MIS), bariatric surgery, laparoscopic surgery, vascular surgery, breast surgery, endourology, gynaecologic surgery, urologic surgery, thoracic surgery, and oncologic surgery. The operative approaches evaluated included laparoscopic, robotic, open, endovascular, and thoracoscopic surgery.

Table 2
Summary of the qualitative studies included in the review.

Study name	Reporting type	Surgery type	Surgical approach	Number of surgeons, n
Moore 2015 [37]	State-Trait Anxiety Inventory	Any	Laparoscopic; Robotic	32
Berquer 2002 [27]	VAS to rate MSK discomfort at different table height levels	NR	Laparoscopic	21
Di Stasi 2017 [36]	NASA-TLX	NR	Laparoscopic	10
Hallbeck 2020 [41]	NASA-TLX	Breast	Open	NR
Kramer 2023 [21]	NASA-TLX	Any	Laparoscopic; Robotic	5
Lau 2020 [42]	NASA-TLX	Any	Laparoscopic; Robotic	16
Law 2020 [43]	NASA-TLX	Colorectal	Laparoscopic; Robotic	7
Aaron 2021 [44]	Self-developed questionnaire	Any	NR	91
Alhusuny 2021 [45]	Nordic Musculoskeletal Questionnaire (NMQ)	Any	Laparoscopic; Robotic	290
Alsabah 2019 [46]	Adapted Nordic Musculoskeletal Questionnaire (NMQ)	Bariatric	Laparoscopic	113
Armijo 2022 [10]	Piper Fatigue Scale-12 (PFS-12)	Any	Laparoscopic	5
Armijo 2019 [9]	Piper Fatigue Scale-12 (PFS-12)	Any	Laparoscopic; Robotic	5
Berguer 1999 [28]	SAGES developed questionnaire	Any	Laparoscopic	27
Cass 2014 [47]	Self-developed questionnaire	Neurosurgery	Laparoscopic	19
Davila 2021 [11]	Self-developed questionnaire	Vascular	Open	16
Dianat 2018 [48]	Nordic Musculoskeletal Questionnaire (NMQ)	NR	NR	312
Healy 2011 [49]	Self-developed questionnaire	Urology	Laparoscopic	600
Hokenstad 2021 [50]	Cornell Musculoskeletal Discomfort Questionnaire	Gynaecology	Robotic	6
Lee 2017 [51]	Self-developed questionnaire	Gynaecology	Robotic	289
Liang 2013 [52]	SAGES developed questionnaire	Urology	Laparoscopic	241
Miller 2012 [53]	SAGES developed questionnaire	Any	Laparoscopic	61
Morandeira-Rivas 2012 [54]	SAGES developed questionnaire	Any	Laparoscopic	78
Norasi 2021 [14]	Self-developed questionnaire, NASA-TLX	Vascular	Open	NR
Plerhoples 2012 [55]	Self-developed questionnaire	Any	Open; Laparoscopic; Robotic	871
Singh 2016 [56]	Body discomfort score & Surgical task load index.	Gynaecology	Open	4
Singh 2019 [57]	Body discomfort score	Gynaecology	Open	4
Sutton 2014 [58]	Self-designed	Any	Open; Laparoscopic; Robotic	314
Szeto 2009 [7]	Self-designed	Any	Open; Laparoscopic	135
Tarr 2015 [59]	Body part discomfort, NASA-TLX	Gynaecology	Laparoscopic; Robotic	16
Welcker 2012 [60]	Self-designed questionnaire	Thoracic	Thoracoscopic	120
Yang 2020 [22]	Wearable sensor & Borg pain scale	Any	NR	53
Yang 202 [40]	Wearable sensor & NASA-TLX questionnaire	Any	Open; Laparoscopic	24
Yu 2017 [17]	Surg-TLX workload	Urology	Robotic	10
Yu 2016 [61]	NASA-TLX workload questionnaires	Any	Laparoscopic	8
Davis 2014 [62]	Self-designed questionnaire	Any	NR	260
Hemal 2001 [63]	Self-designed questionnaire	Urology	Open; Laparoscopic	204
Indramohan 2012 [64]	Self-designed questionnaire	Any	Open; Laparoscopic	200
Park 2009 [65]	Self-designed questionnaire	Any	Open; Laparoscopic	317
Kaya 2008 [66]	Self-designed questionnaire	Any	Laparoscopic	82
Santos-Carreras 2012 [67]	Self-designed questionnaire	Any	Open; Laparoscopic; Robotic	49
Soueid 2009 [68]	Self-designed questionnaire	Any	NR	130
Szeto 2010 [7]	EMG & Self-designed questionnaire	Vascular	Open; Laparoscopic	25
Craven 2013 [69]	RULA & Strain Index (SI)	Gynaecology	Robotic	5
Graversen 2011 [70]	Self-designed questionnaire	Urology	Laparoscopic	11
Haramis 2010 [71]	Self-designed questionnaire	Urology	Laparoscopic	NR
Klein 2010 [72]	Self-designed questionnaire	NR	Open; Laparoscopic	10
Nguyen 200 [6]	Neck, trunk, shoulder, elbow, and wrist movements using predefined criteria developed by the Department of Physical Therapy.	NR	Open; Laparoscopic	5
Reddy 2011 [73]	Self-designed questionnaire	NR	Laparoscopic	7
Hilt 2024 [74]	RULA and Surgery Task Load Index	Bariatric	Robotic, laparoscopic	5

3.2.3. *Study types and measures of strain*

The review included various study designs, ranging from surveys and interventional studies to prospective randomized evaluations and pilot studies. Sample sizes varied significantly, from small-scale surveys to large-scale investigations involving hundreds of surgeons. Strain measures were diverse, including muscle effort, workload, discomfort, pain, and posture, often quantified through self-assessment scales, motion tracking sensors, or physiological measurements. These varied methodologies ensured a comprehensive understanding of the ergonomic challenges faced by surgeons.

4. Impact on surgeons

Prolonged surgeries were particularly associated with an increased risk of musculoskeletal injuries, including vertebral disc prolapse [47]. The use of robotic surgery was identified to improve ergonomic issues compared to laparoscopic surgery, but still posed challenges, particularly with muscle activation, as described above. Manufacturers of robotic systems claim that being seated at a console improves surgeon safety with regards to injury, fatigue, and muscle exertion [76].

Gender-specific differences in muscle effort and ergonomic strain were noted, suggesting that ergonomic designs need to consider these differences to ensure equity and safety for all surgeons [10,58]. For instance, women experienced more ergonomic strain compared to men, with increased muscle activation during laparoscopic surgery, particularly of the upper trapezius and extensor digitorum, measured using EMG [10]. Smaller glove sizes (more commonly in women) were associated with increased shoulder and neck strain [58]. Even for the same glove size, women self-reported more discomfort in their upper limbs, neck and back compared to men [58].

Effective interventions such as ergonomic console configurations and gel foot pads were highlighted as beneficial in reducing physical strain [70]. These tools helped improve surgeon comfort and reduced the risk of musculoskeletal injuries during prolonged surgical procedures.

5. Discussion

Ergonomic strain amongst surgeons is a potential occupational risk. Whilst it is not possible to define an acceptable level of ergonomic strain, it is important to explore the nature of strain and the ways in which this can be improved. This review aims to explore the ways in which strain can be measured in the context of open and minimally invasive abdominal and thoracic surgery.

The key messages highlighted from this review are:

1. Minimally invasive surgery recruits a different set of muscles compared to open surgery, with different ergonomic challenges. The learning curves of minimally invasive surgery may increase cognitive strain in the short-term but robotic surgery has lower overall cognitive and cardiovascular strain. More research is required to explore the ergonomic impact on the assisting 'table' surgeon in robotic cases.
2. Hand size or hand size in the context of gender can have notable ergonomic implications and is an important area of instrument development
3. Areas for future research include the role of learning curves and surgeon experience on ergonomic strain and the impact of patient factors, environmental factors and a surgeon's pre-existing health on ergonomic strain

5.1. *Minimally invasive surgery versus open surgery*

Traditional open surgery has been shown to be the most strenuous in terms of muscle activation and awkward posturing [7,14,15,40]. The advent of minimally invasive surgery has resulted in recruitment of a different set of muscle groups, rather than an overall improvement in musculoskeletal strain [6,9]. Laparoscopic surgery is noted to have less neck and torso muscle activation but more upper limb muscle activation and posturing [6]. It is interesting to note that the learning curve of laparoscopic surgery results in substantial cognitive strain [29]. Laparo-endoscopic single incision surgery resulted in more cognitive stress compared to conventional laparoscopic surgery, possibly because the former procedure is less commonly performed [29].

Robotic surgery was introduced and marketed as being more ergonomically comfortable. The data was conflicting in terms of muscle activation when compared to laparoscopic surgery but was reported to cause less cognitive and cardiovascular stress [9,21,12]. Whilst this may suggest that the console surgeon was likely to experience less strain overall, the assisting table surgeon was assisting as per conventional laparoscopic surgery and therefore, prone to the associated strain [17].

5.2. *Impact of gender/hand-size*

Gender differences in ergonomic strain and muscle effort raises important questions in terms of equality, particularly in the design of surgical instruments. Women are found to exhibit increased musculoskeletal strain and discomfort, with increased muscle activation during laparoscopic surgery [10,58]. These ergonomic considerations are crucial when reviewing the impact of the operative environment on different genders. Although not particularly explored in the literature, it would be interesting to consider the role of robotic surgery for female surgeons or surgeons of any gender with small size hands as the robotic console only has finger sockets rather than laparoscopic instruments which may not accommodate different sizes or shapes of hands.

5.3. *Level of experience*

There is a paucity of data correlating learning curves or level of expertise with strain as this would perhaps suggest that surgical training should also encompass ergonomic training and positioning. Simulation studies show that table height adjustments, monitor positions and the types of surgical instrument (e.g. ratcheted) can support surgeons in making conscious choices to be comfortable whilst operating [24,25,27].

5.4. *Strengths and limitations of the review*

The strength of this review is that it consolidates the key ergonomic concerns for general surgeons across all modalities, including robotic surgery and draws comparisons between laparoscopic and robotic surgery. The limitations of this review are that there is notable variation when measuring strain and it is very difficult to draw meaningful comparisons across these. The long-term nature and impact of strain on the surgeon makes it methodologically challenging to design studies that explore this comprehensively. Furthermore, there are many other aspects that significantly impact strain – table height, level of training or experience, environmental factors such as the theatre environment and situational awareness as well as patient factors such as their body mass index, technical factors which might make operations more difficult. For instance, Hilt et al. demonstrated that robotic surgery resulted in lower ergonomic stress compared to laparoscopic surgery in the context of bariatric operations such as sleeve gastrectomy and Roux-en-Y gastric bypass [74]. The role of gender is also a worthy area of surgical exploration. There is also little information on the impact of surgeon ergonomic strain on the patient [62]. These highlight key areas for future research.

There is a lot more scope to incorporate surgeon comfort and ergonomics in instrument and theatre design. Despite plenty of research into the nature of surgeon strain, there are few tangible measures to improve this to improve performance and longevity of career.

Sources of financial support

Nadia Guidozzi – Ryan Hill Research Foundation.

Sivesh Kathir Kamarajah – National Institute for Health and Care Research.

Sheraz R. Markar – National Institute for Health and Care Research.

Conflict of interest statement

None of the authors have any conflicts of interest to declare.

References

[1] Stucky CH, Cromwell KD, Voss RK, Chiang YJ, Woodman K, Lee JE, Cormier JN. Surgeon symptoms, strain, and selections: systematic review and meta-analysis of surgical ergonomics. Ann Med Surg (Lond) 2018 Jan 9;27:1–8. https://doi.org/10.1016/j.amsu.2017.12.013. PMID: 29511535; PMCID: PMC5832650.

[2] Franasiak J, Ko EM, Kidd J, et al. Physical strain and urgent need for ergonomic training among gynecologic oncologists who perform minimally invasive surgery. Gynecol Oncol 2012;126(3):437–42.

[3] McDonald ME, Ramirez PT, Munsell MF, et al. Physician pain and discomfort during minimally invasive gynecologic cancer surgery. Gynecol Oncol 2014;134 (2):243–7.

[4] Meltzer AJ, Hallbeck MS, Morrow MM, Lowndes BR, Davila VJ, Stone WM, Money SR. Measuring ergonomic risk in operating surgeons by using wearable technology. JAMA Surg 2020 May 1;155(5):444–6. https://doi.org/10.1001/jamasurg.2019.6384. PMID: 32159745; PMCID: PMC7066524.

[5] Adams SR, Hacker MR, McKinney JL, Elkadry EA, Rosenblatt PL. _Musculoskeletal pain in gynecologic surgeons. J Minim Invasive Gynecol 2013;20(5):656–60.

[6] Nguyen NT, Ho HS, Smith WD, et al. An ergonomic evaluation of surgeons' axial skeletal and upper extremity movements during laparoscopic and open surgery. Am J Surg 2001;182(6):720–4.

[7] Szeto GP, Ho P, Ting AC, Poon JT, Tsang RC, Cheng SW. A study of surgeons' postural muscle activity during open, laparoscopic, and endovascular surgery. Surg Endosc 2010;24(7):1712–21.

[8] Yang L, Wang T, Weidner TK, Madura 2nd JA, Morrow MM, Hallbeck MS. Intraoperative musculoskeletal discomfort and risk for surgeons during open and laparoscopic surgery. Surg Endosc 2021 Nov;35(11):6335–43. https://doi.org/10.1007/s00464-020-08085-3. Epub 2020 Oct 20. PMID: 33083930.

[9] Armijo PR, Huang CK, High R, Leon M, Siu KC, Oleynikov D. Ergonomics of minimally invasive surgery: an analysis of muscle effort and fatigue in the operating room between laparoscopic and robotic surgery. Surg Endosc 2019 Jul; 33(7):2323–31. https://doi.org/10.1007/s00464-018-6515-3. Epub 2018 Oct 19. PMID: 30341653.

[10] Armijo PR, Flores L, Pokala B, Huang CK, Siu KC, Oleynikov D. Gender equity in ergonomics: does muscle effort in laparoscopic surgery differ between men and women? Surg Endosc 2022 Jan;36(1):396–401. https://doi.org/10.1007/s00464-021-08295-3. Epub 2021 Jan 25. PMID: 33492502.

[11] Davila VJ, Meltzer AJ, Fortune E, Morrow MMB, Lowndes BR, Linden AR, Hallbeck MS, Money SR. Intraprocedural ergonomics of vascular surgeons. J Vasc Surg 2021 Jan;73(1):301–8. https://doi.org/10.1016/j.jvs.2020.04.523. Epub 2020 May 23. PMID: 32450279.

[12] Dalager T, Jensen PT, Eriksen JR, Jakobsen HL, Mogensen O, Søgaard K. Surgeons' posture and muscle strain during laparoscopic and robotic surgery. Br J Surg 2020 May;107(6):756–66. https://doi.org/10.1002/bjs.11394. Epub 2020 Jan 10. PMID: 31922258.

[13] Thurston T, Dolan JP, Husain F, Stroud A, Funk K, Borzy C, Zhu X. Assessment of muscle activity and fatigue during laparoscopic surgery. Surg Endosc 2022 Sep;36 (9):6672–8. https://doi.org/10.1007/s00464-021-08937-6. Epub 2022 Jan 16. Erratum in: Surg Endosc. 2022 Nov;36(11):8697. doi: 10.1007/s00464-022-09619-7. PMID: 35034217.

[14] Norasi H, Tetteh E, Money SR, Davila VJ, Meltzer AJ, Morrow MM, Fortune E, Mendes BC, Hallbeck MS. Intraoperative posture and workload assessment in vascular surgery. Appl Ergon 2021 Apr;92:103344. https://doi.org/10.1016/j.apergo.2020.103344. Epub 2020 Dec 21. PMID: 33359926.

[15] Fan X, Forsman M, Yang L, Lind CM, Kjellman M. Surgeons' physical workload in open surgery versus robot-assisted surgery and nonsurgical tasks. Surg Endosc 2022 Nov;36(11):8178–94. https://doi.org/10.1007/s00464-022-09256-0. Epub 2022 May 19. PMID: 35589973; PMCID: PMC9613719.

[16] Abdelrahman AM, Bingener J, Yu D, Lowndes BR, Mohamed A, McConico AL, Hallbeck MS. Impact of single-incision laparoscopic cholecystectomy (SILC) versus conventional laparoscopic cholecystectomy (CLC) procedures on surgeon stress and workload: a randomized controlled trial. Surg Endosc 2016 Mar;30(3): 1205–11. https://doi.org/10.1007/s00464-015-4332-5. Epub 2015 Jul 21. PMID: 26194249; PMCID: PMC4721929.

[17] Yu D, Dural C, Morrow MM, Yang L, Collins JW, Hallbeck S, Kjellman M, Forsman M. Intraoperative workload in robotic surgery assessed by wearable motion tracking sensors and questionnaires. Surg Endosc 2017 Feb;31(2):877–86. https://doi.org/10.1007/s00464-016-5047-y. Epub 2016 Aug 5. PMID: 27495330.

[18] Bigham JJ, Chang EK, Sorensen M, Chansky HA, Telfer S. Using wearable technology to measure the association between neck posture and pain during urologic open and robotic surgery. J Endourol 2021 Nov;35(11):1710–5. https://doi.org/10.1089/end.2021.0260. Epub 2021 Sep 17. PMID: 33940950.

[19] Heemskerk J, Zandbergen HR, Keet SW, Martijnse I, van Montfort G, Peters RJ, Svircevic V, Bouwman RA, Baeten CG, Bouvy ND. Relax, it's just laparoscopy! A prospective randomized trial on heart rate variability of the surgeon in robot-assisted versus conventional laparoscopic cholecystectomy. Dig Surg 2014;31(3): 225–32. https://doi.org/10.1159/000365580. Epub 2014 Sep 25. PMID: 25277215.

[20] Kraemer B, Seibt R, Stoffels AK, Rothmund R, Brucker SY, Rieger MA, Steinhilber B. An ergonomic field study to evaluate the effects of a rotatable handle piece on muscular stress and fatigue as well as subjective ratings of usability, wrist posture and precision during laparoscopic surgery: an explorative pilot study. Int Arch Occup Environ Health 2018 Nov;91(8):1021–9. https://doi.org/10.1007/s00420-018-1344-1. Epub 2018 Aug 4. PMID: 30078157.

[21] Krämer B, Neis F, Reisenauer C, Walter C, Brucker S, Wallwiener D, Seibt R, Gabriel J, Rieger MA, Steinhilber B. Save our surgeons (SOS) - an explorative comparison of surgeons' muscular and cardiovascular demands, posture, perceived workload and discomfort during robotic vs. laparoscopic surgery. Arch Gynecol Obstet 2023 Mar;307(3):849–62. https://doi.org/10.1007/s00404-022-06841-5. Epub 2022 Nov 19. PMID: 36401096; PMCID: PMC9676911.

[22] Yang L, Money SR, Morrow MM, Lowndes BR, Weidner TK, Fortune E, Davila VJ, Meltzer AJ, Stone WM, Hallbeck MS. Impact of procedure type, case duration, and adjunctive equipment on surgeon intraoperative musculoskeletal discomfort. J Am Coll Surg 2020 Apr;230(4):554–60. https://doi.org/10.1016/j.jamcollsurg.2019.12.035. Epub 2020 Mar 15. PMID: 32220445.

[23] Lawson EH, Curet MJ, Sanchez BR, Schuster R, Berguer R. Postural ergonomics during robotic and laparoscopic gastric bypass surgery: a pilot project. J Robot Surg 2007;1(1):61–7. https://doi.org/10.1007/s11701-007-0016-z. Epub 2007 Feb 10. PMID: 25484939; PMCID: PMC4247428.

[24] Manasnayakorn S, Cuschieri A, Hanna GB. Ergonomic assessment of optimum operating table height for hand-assisted laparoscopic surgery. Surg Endosc 2009 Apr;23(4):783–9. https://doi.org/10.1007/s00464-008-0068-9. Epub 2008 Jul 16. PMID: 18629584.

[25] Matern U, Faist M, Kehl K, Giebmeyer C, Buess G. Monitor position in laparoscopic surgery. Surg Endosc 2005 Mar;19(3):436–40. https://doi.org/10.1007/s00464-004-9030-7. Epub 2005 Jan 10. PMID: 15645325.

[26] van der Schatte Olivier RH, Van't Hullenaar CD, Ruurda JP, Broeders IA. Ergonomics, user comfort, and performance in standard and robot-assisted laparoscopic surgery. Surg Endosc 2009 Jun;23(6):1365–71. https://doi.org/10.1007/s00464-008-0184-6. Epub 2008 Oct 15. PMID: 18855053; PMCID: PMC2687080.

[27] Berquer R, Smith WD, Davis S. An ergonomic study of the optimum operating table height for laparoscopic surgery. Surg Endosc 2002 Mar;16(3):416–21. https://doi.org/10.1007/s00464-001-8190-y. Epub 2001 Nov 16. PMID: 11928019.

[28] Berguer R, Forkey DL, Smith WD. Ergonomic problems associated with laparoscopic surgery. Surg Endosc 1999 May;13(5):466–8. https://doi.org/10.1007/pl00009635. PMID: 10227943.

[29] Berguer R, Smith WD, Chung YH. Performing laparoscopic surgery is significantly more stressful for the surgeon than open surgery. Surg Endosc 2001 Oct;15(10): 1204–7. https://doi.org/10.1007/s004640080030. PMID: 11727101.

[30] Berguer R, Forkey DL, Smith WD. The effect of laparoscopic instrument working angle on surgeons' upper extremity workload. Surg Endosc 2001 Sep;15(9): 1027–9. https://doi.org/10.1007/s00464-001-0019-1. Epub 2001 Jun 12. PMID: 11443477.

[31] Berguer R, Chen J, Smith WD. A comparison of the physical effort required for laparoscopic and open surgical techniques. Arch Surg 2003 Sep;138(9):967–70. https://doi.org/10.1001/archsurg.138.9.967. PMID: 12963653.

[32] Berguer R, Smith W. An ergonomic comparison of robotic and laparoscopic technique: the influence of surgeon experience and task complexity. J Surg Res 2006 Jul;134(1):87–92. https://doi.org/10.1016/j.jss.2005.10.003. Epub 2005 Dec 27. PMID: 16376941.

[33] Marquetand J, Gabriel J, Seibt R, Grimm A, Steinhilber B. Ergonomics for surgeons - prototype of an external surgeon support system reduces muscular activity and fatigue. J Electromyogr Kinesiol 2021 Oct;60:102586. https://doi.org/10.1016/j.jelekin.2021.102586. Epub 2021 Aug 14. PMID: 34450379.

[34] Wright HC, Gheordunescu G, O'Laughlin K, Sun A, Fulla J, Kachroo N, De S. Ergonomics in the OR: an electromyographic evaluation of common muscle groups used during simulated flexible ureteroscopy - a pilot study. Urology 2022 Dec;170: 66–72. https://doi.org/10.1016/j.urology.2022.08.028. Epub 2022 Sep 1. PMID: 36057324.

[35] Morales JM, Ruiz-Rabelo JF, Diaz-Piedra C, Di Stasi LL. Detecting mental workload in surgical teams using a wearable single-channel electroencephalographic device. J Surg Educ 2019 Jul-Aug;76(4):1107–15. https://doi.org/10.1016/j.jsurg.2019.01.005. Epub 2019 Jan 26. PMID: 30691989.

[36] Di Stasi LL, Díaz-Piedra C, Ruiz-Rabelo JF, Rieiro H, Sanchez Carrion JM, Catena A. Quantifying the cognitive cost of laparo-endoscopic single-site surgeries: gaze-based indices. Appl Ergon 2017 Nov;65:168–74. https://doi.org/10.1016/j.apergo.2017.06.008. Epub 2017 Jun 27. PMID: 28802436.

[37] Moore LJ, Wilson MR, Waine E, McGrath JS, Masters RS, Vine SJ. Robotically assisted laparoscopy benefits surgical performance under stress. J Robot Surg 2015 Dec;9(4):277–84. https://doi.org/10.1007/s11701-015-0527-y. Epub 2015 Aug 2. PMID: 26530839.

[38] Steinhilber B, Seibt R, Reiff F, Rieger MA, Kraemer B, Rothmund R. Effect of a laparoscopic instrument with rotatable handle piece on biomechanical stress during laparoscopic procedures. Surg Endosc 2016 Jan;30(1):78–88. https://doi.org/10.1007/s00464-015-4164-3. Epub 2015 Apr 1. PMID: 25829062.

[39] Quick NE, Gillette JC, Shapiro R, Adrales GL, Gerlach D, Park AE. The effect of using laparoscopic instruments on muscle activation patterns during minimally invasive surgical training procedures. Surg Endosc 2003 Mar;17(3):462–5. https://doi.org/10.1007/s00464-002-8530-6. Epub 2002 Oct 29. PMID: 12399872.

[40] Wang R, Liang Z, Zihni AM, et al. Which causes more ergonomic stress: laparoscopic or open surgery? Surg Endosc 2017;31:3286–90. https://doi.org/10.1007/s00464-016-5360-5.

[41] Hallbeck MS, Law KE, Lowndes BR, Linden AR, Morrow M, Blocker RC, Cain SM, Degnim AC, Hieken TJ, Jakub JW, Racz JM, Farley DR, Nelson H, Boughey JC. Workload differentiates breast surgical procedures: NSM associated with higher

workload demand than SSM. Ann Surg Oncol 2020 May;27(5):1318–26. https://doi.org/10.1245/s10434-019-08159-0. Epub 2020 Jan 8. PMID: 31916090; PMCID: PMC7138769.

[42] Lau E, Alkhamesi NA, Schlachta CM. Impact of robotic assistance on mental workload and cognitive performance of surgical trainees performing a complex minimally invasive suturing task. Surg Endosc 2020 Jun;34(6):2551–9. https://doi.org/10.1007/s00464-019-07038-9. Epub 2019 Sep 3. PMID: 31482359.

[43] Law KE, Lowndes BR, Kelley SR, Blocker RC, Larson DW, Hallbeck MS, Nelson H. NASA-task load index differentiates surgical approach: opportunities for improvement in colon and rectal surgery. Ann Surg 2020 May;271(5):906–12. https://doi.org/10.1097/SLA.0000000000003173. PMID: 30614878.

[44] Aaron KA, Vaughan J, Gupta R, Ali NE, Beth AH, Moore JM, Ma Y, Ahmad I, Jackler RK, Vaisbuch Y. The risk of ergonomic injury across surgical specialties. PLoS One 2021 Feb 9;16(2):e0244868. https://doi.org/10.1371/journal.pone.0244868. PMID: 33561117; PMCID: PMC7872272.

[45] Alhusuny A, Cook M, Khalil A, Johnston V. Visual symptoms, Neck/shoulder problems and associated factors among surgeons performing Minimally Invasive Surgeries (MIS): a comprehensive survey. Int Arch Occup Environ Health 2021 Jul; 94(5):959–79. https://doi.org/10.1007/s00420-020-01642-2. Epub 2021 Jan 29. PMID: 33515063.

[46] AlSabah S, Al Haddad E, Khwaja H. The prevalence of musculoskeletal injuries in bariatric surgeons. Surg Endosc 2019 Jun;33(6):1818–27. https://doi.org/10.1007/s00464-018-6460-1. Epub 2018 Sep 24. PMID: 30251136.

[47] Cass GK, Vyas S, Akande V. Prolonged laparoscopic surgery is associated with an increased risk of vertebral disc prolapse. J Obstet Gynaecol 2014 Jan;34(1):74–8. https://doi.org/10.3109/01443615.2013.831048. PMID: 24359056.

[48] Dianat I, Bazazan A, Souraki Azad MA, Salimi SS. Work-related physical, psychosocial and individual factors associated with musculoskeletal symptoms among surgeons: implications for ergonomic interventions. Appl Ergon 2018 Feb; 67:115–24. https://doi.org/10.1016/j.apergo.2017.09.011. Epub 2017 Oct 7. PMID: 29122182.

[49] Healy KA, Pak RW, Cleary RC, Colon-Herdman A, Bagley DH. Hand problems among endourologists. J Endourol 2011 Dec;25(12):1915–20. https://doi.org/10.1089/end.2011.0128. Epub 2011 Oct 17. PMID: 22004843.

[50] Hokenstad ED, Hallbeck MS, Lowndes BR, Morrow MM, Weaver AL, McGree M, Glaser GE, Occhino JA. Ergonomic robotic console configuration in gynecologic surgery: an interventional study. J Minim Invasive Gynecol 2021 Apr;28(4):850–9. https://doi.org/10.1016/j.jmig.2020.07.017. Epub 2020 Jul 28. PMID: 32735942.

[51] Lee MR, Lee GI. Does a robotic surgery approach offer optimal ergonomics to gynecologic surgeons?: a comprehensive ergonomics survey study in gynecologic robotic surgery. J Gynecol Oncol 2017 Sep;28(5):e70. https://doi.org/10.3802/jgo.2017.28.e70. Epub 2017 Jun 23. PMID: 28657231; PMCID: PMC5540729.

[52] Liang B, Qi L, Yang J, Cao Z, Zu X, Liu L, Wang L. Ergonomic status of laparoscopic urologic surgery: survey results from 241 urologic surgeons in China. PLoS One 2013 Jul 31;8(7):e70423. https://doi.org/10.1371/journal.pone.0070423. PMID: 23936202; PMCID: PMC3729835.

[53] Miller K, Benden M, Pickens A, Shipp E, Zheng Q. Ergonomics principles associated with laparoscopic surgeon injury/illness. Hum Factors 2012 Dec;54(6):1087–92. https://doi.org/10.1177/0018720812451046. PMID: 23397816.

[54] Morandeira-Rivas A, Millán-Casas L, Moreno-Sanz C, Herrero-Bogajo ML, Tenías-Burillo JM, Giménez-Salillas L. Ergonomics in laparoendoscopic single-site surgery: survey results. J Gastrointest Surg 2012 Nov;16(11):2151–9. https://doi.org/10.1007/s11605-012-2021-4. Epub 2012 Sep 7. PMID: 22956405.

[55] Plerhoples TA, Hernandez-Boussard T, Wren SM. The aching surgeon: a survey of physical discomfort and symptoms following open, laparoscopic, and robotic surgery. J Robot Surg 2012 Mar;6(1):65–72. https://doi.org/10.1007/s11701-011-0330-3. Epub 2011 Dec 13. PMID: 27637981.

[56] Singh R, Carranza Leon DA, Morrow MM, Vos-Draper TL, Mc Gree ME, Weaver AL, Woolley SM, Hallbeck S, Gebhart JB. Effect of chair types on work-related musculoskeletal discomfort during vaginal surgery. Am J Obstet Gynecol 2016 Nov;215(5):648.e1–9. https://doi.org/10.1016/j.ajog.2016.06.016. Epub 2016 Jun 16. PMID: 27319363.

[57] Singh R, Yurteri-Kaplan LA, Morrow MM, Weaver AL, McGree ME, Zhu X, Paquet VL, Gebhart JB, Hallbeck S. Sitting versus standing makes a difference in musculoskeletal discomfort and postural load for surgeons performing vaginal surgery. Int Urogynecol J 2019 Feb;30(2):231–7. https://doi.org/10.1007/s00192-018-3619-1. Epub 2018 Apr 18. PMID: 29671032.

[58] Sutton E, Irvin M, Zeigler C, Lee G, Park A. The ergonomics of women in surgery. Surg Endosc 2014 Apr;28(4):1051–5. https://doi.org/10.1007/s00464-013-3281-0. PMID: 24232047.

[59] Tarr ME, Brancato SJ, Cunkelman JA, Polcari A, Nutter B, Kenton K. Comparison of postural ergonomics between laparoscopic and robotic sacrocolpopexy: a pilot study. J Minim Invasive Gynecol 2015 Feb;22(2):234–8. https://doi.org/10.1016/j.jmig.2014.10.004. Epub 2014 Oct 12. PMID: 25315401.

[60] Welcker K, Kesieme EB, Internullo E, Kranenburg van Koppen LJ. Ergonomics in thoracoscopic surgery: results of a survey among thoracic surgeons. Interact Cardiovasc Thorac Surg 2012 Aug;15(2):197–200. https://doi.org/10.1093/icvts/ivs173. Epub 2012 May 14. PMID: 22586071; PMCID: PMC3397748.

[61] Yu D, Lowndes B, Morrow M, Kaufman K, Bingener J, Hallbeck S. Impact of novel shift handle laparoscopic tool on wrist ergonomics and task performance. Surg Endosc 2016 Aug;30(8):3480–90. https://doi.org/10.1007/s00464-015-4634-7. Epub 2015 Nov 5. PMID: 26541720; PMCID: PMC4860168.

[62] Davis WT, Fletcher SA, Guillamondegui OD. Musculoskeletal occupational injury among surgeons: effects for patients, providers, and institutions. J Surg Res 2014 Jun 15;189(2):207–212.e6. https://doi.org/10.1016/j.jss.2014.03.013. Epub 2014 Mar 13. PMID: 24721601.

[63] Hemal AK, Srinivas M, Charles AR. Ergonomic problems associated with laparoscopy. J Endourol 2001 Jun;15(5):499–503. https://doi.org/10.1089/089277901750299294. PMID: 11465329.

[64] Indramohan VP, Ashford R, Khan S, Lintern M. Are surgeon's content with the current surgical headgear systems? J Med Eng Technol 2012 Oct;36(7):366–71. https://doi.org/10.3109/03091902.2012.712203. Epub 2012 Sep 3. PMID: 22943636.

[65] Park A, Lee G, Seagull FJ, Meenaghan N, Dexter D. Patients benefit while surgeons suffer: an impending epidemic. J Am Coll Surg 2010 Mar;210(3):306–13. https://doi.org/10.1016/j.jamcollsurg.2009.10.017. Epub 2009 Dec 24. PMID: 20193893.

[66] Kaya OI, Moran M, Ozkardes AB, Taskin EY, Seker GE, Ozmen MM. Ergonomic problems encountered by the surgical team during video endoscopic surgery. Surg Laparosc Endosc Percutaneous Tech 2008 Feb;18(1):40–4. https://doi.org/10.1097/SLE.0b013e3181569ee2. PMID: 18287981.

[67] Santos-Carreras L, Hagen M, Gassert R, Bleuler H. Survey on surgical instrument handle design: ergonomics and acceptance. Surg Innov 2012 Mar;19(1):50–9. https://doi.org/10.1177/1553350611413611. Epub 2011 Aug 25. PMID: 21868419.

[68] Soueid A, Oudit D, Thiagarajah S, Laitung G. The pain of surgery: pain experienced by surgeons while operating. Int J Surg 2010;8(2):118–20. https://doi.org/10.1016/j.ijsu.2009.11.008. Epub 2009 Nov 24. PMID: 19944192.

[69] Craven R, Franasiak J, Mosaly P, Gehrig PA. Ergonomic deficits in robotic gynecologic oncology surgery: a need for intervention. J Minim Invasive Gynecol 2013 Sep-Oct;20(5):648–55. https://doi.org/10.1016/j.jmig.2013.04.008. Epub 2013 Jun 5. PMID: 23747116.

[70] Graversen JA, Korets R, Mues AC, Katsumi HK, Badani KK, Landman J, Gupta M. Prospective randomized evaluation of gel mat foot pads in the endoscopic suite. J Endourol 2011 Nov;25(11):1793–6. https://doi.org/10.1089/end.2011.0155. Epub 2011 Oct 3. PMID: 21967319.

[71] Haramis G, Rosales JC, Palacios JM, Okhunov Z, Mues AC, Lee D, Badani K, Gupta M, Landman J. Prospective randomized evaluation of FOOT gel pads for operating room staff COMFORT during laparoscopic renal surgery. Urology 2010 Dec;76(6):1405–8. https://doi.org/10.1016/j.urology.2010.01.018. Epub 2010 Mar 28. PMID: 20350745.

[72] Klein M, Andersen LP, Alamili M, Gögenur I, Rosenberg J. Psychological and physical stress in surgeons operating in a standard or modern operating room. Surg Laparosc Endosc Percutaneous Tech 2010 Aug;20(4):237–42. https://doi.org/10.1097/SLE.0b013e3181ed851d. PMID: 20729692.

[73] Reddy PP, Reddy TP, Roig-Francoli J, Cone L, Sivan B, DeFoor WR, Gaitonde K, Noh PH. The impact of the alexander technique on improving posture and surgical ergonomics during minimally invasive surgery: pilot study. J Urol 2011 Oct;186(4 Suppl):1658–62. https://doi.org/10.1016/j.juro.2011.04.013. Epub 2011 Aug 19. PMID: 21855928.

[74] Hilt L, Sherman B, Tan WH, Lak K, Gould JC, Kindel TL, Higgins RM. Bariatric surgeon ergonomics: a comparison of laparoscopy and robotics. J Surg Res 2024 Mar;295:864–73. https://doi.org/10.1016/j.jss.2023.08.045. Epub 2023 Nov 13. PMID: 37968140.

[75] Hotton J, Bogart E, Le Deley MC, Lambaudie E, Narducci F, Marchal F. Ergonomic assessment of the surgeon's physical workload during robot-assisted versus standard laparoscopy in a French multicenter randomized trial (ROBOGYN-1004 trial). Ann Surg Oncol 2023 Feb;30(2):916–23. https://doi.org/10.1245/s10434-022-12548-3. Epub 2022 Sep 29. PMID: 36175710.

[76] Surgical Intuitive. Intuitive's immersive da Vinci surgical console helps make surgeons' work easier. Available from, https://www.intuitive.com/en-us/about-us/newsroom/immersive-console; 2024.